Appendix A

Guidelines for Thermographic Inspection of Concrete Bridges

Development of Hand-held Thermographic Inspection Technologies

Revised Guidelines for Thermographic Inspection of Concrete Bridges

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Revised January, 2014

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Guidelines for Thermographic Inspection of Concrete Bridges

The following are suggested guidelines for the thermographic inspection of highway bridges, based on the results of the research.

1.0 Surfaces exposed to Direct Solar Loading

1.1 Solar loading

1.1.1 Conduct inspections on days when there is direct, uninterrupted solar loading. Cloud cover should be minimal.

1.1.2 Summer days are preferred over winter days due to the more intense and longer solar exposure.

1.2 Wind Conditions

1.2.1 Lower wind speeds will result in improved thermal contrast for surfaces exposed to solar loading. In general, wind reduces the effect of radiant heating from the sun and reduces the thermal contrast resulting from subsurface defects.

1.2.2 Average wind speeds should be 15 mph or less prior to and during the inspection period. These data can be obtained based on National Weather Service (NWS) hourly wind reports[(5.1)].

1.3 Inspection Period

1.3.1 Inspections should be conducted starting no sooner than 4 hours after sunrise to allow for thermal contrast to develop when anticipated depth of the delamination is approximately 2 in. from the surface of the concrete. The useful inspection period is expected to last approximately 6 hours. If the anticipated depth is 3 inches, inspection should be conducted starting 5 to 6 hours after sunrise. The useful inspection period will last approximately 5 hours[(5.2)].

2.0 . Shaded Surfaces – Daytime inspection

2.1 Ambient Temperature Changes:

2.1.1 Inspection should be conducted on days when the ambient temperature differential is expected to be at least 15°F.

2.1.2 The measured ambient temperature differential should be at least 10°F within the first 6 hours after sunrise.

2.1.3 In general, more rapid increases in ambient temperature will result in improved thermal contrast.

2.1.4 When ambient temperatures begin to decrease, thermal contrasts will also begin to decrease for a 2 in. deep delamination.

2.1.5 Local environment: The indicated ambient temperature differentials must be applied at the surface to be inspected. If the location and geometry of the bridge results in reduced ambient temperature changes at the surface to be inspected, this should be considered in determining if adequate conditions exist for detection of subsurface defects. A simple temperature monitoring device that stores hourly temperatures can be used to assess the local conditions at a bridge.

2.2 Wind Speed

2.2.1 A practical limit of 25 mph average wind speed is suggested, based on NWS data[5.1]. High average wind speeds are not necessarily detrimental to the development of thermal contrast for shady conditions.

2.3 Inspection Periods

2.3.1 Inspections should be conducted starting 4 to 5 hours after sunrise to allow for thermal contrast to develop when anticipated depth of the delamination is approximately 2 in. from the surface of the concrete. The useful inspection period is expected to last approximately 8 hours. If the anticipated depth is 3 in., inspection should be conducted starting approximately 7 hours after sunrise. The useful inspection period is expected to last approximately 4 hours.

2.4 Deck Soffit Inspections

2.4.1 Solar loading on the surface of a bridge deck affects the detection of delamination in the soffit of the deck due to thermal conduction. As a consequence, delamination in the soffit may appear colder than surrounding concrete rather than warmer, as would typically be expected during a warming cycle. The approximate timing of when this may occur can be estimated with knowledge of the deck thickness (*t*, in.). The reversal, from warm to cold, of a delamination in the soffit will occur "*t*" hours after the solar loading begins. For example, for a bridge deck 7 inches thick, assuming sunrise at 6 am, the reversal will occur at ~1 pm. Care should be taken in the preceding 2 hrs., because thermal contrast may be minimal during this time period.

3.0 Shaded Surfaces – Nighttime inspections

3.1 Ambient Temperature Changes:

3.1.1 Inspection should be conducted on nights when the ambient temperature differential is expected to be at least -15°F. This value is measured from the highest temperature in the afternoon to the coldest temperature in the overnight period.

3.1.2 The measured ambient temperature differential should be at least -10°F during the 6 hours preceding sunset for the previous day.

3.1.3 In general, more rapid decreases in ambient temperature will result in improved thermal contrast.

3.1.4 When ambient temperatures begin to increase, thermal contrasts will begin to decrease for a 2 in. deep delamination.

3.2 Local environment: The indicated ambient temperature differentials must be applied at the surface to be inspected. If the location and geometry of the bridge result in reduced ambient temperature changes at the surface to be inspected, this should be considered in determining if adequate conditions exist for detection of subsurface defects.

3.3 Wind Speed

3.3.1 A practical limit of 25 mph average wind speed is suggested, based on NWS data(5.1). High average wind speeds are not necessarily detrimental to the development of thermal contrast for shady conditions.

3.4 Inspection Periods

3.4.1 Inspections should be conducted starting 1 hour after sunset when the anticipated depth of the delamination is approximately 2 in. from the surface of the concrete. The useful inspection period is expected to last approximately 9 hours. If the anticipated depth is 3 inches, inspection should be conducted starting approximately 3 hours after sunset. The useful inspection period is expected to last approximately 7 hours.

4.0 Camera Settings

4.1 Focus: To allow for small temperature contrasts at delaminations to be detected, cameras should be properly focused on the inspection surface. Placement of a regularly shaped object, such as a tool or a coin, on the surface to be inspected can be used to assist in focusing the camera properly. Well defined edges or an object on the structure surface, such as a utility connection, can also be used.

4.2 Level and span: Level and span settings for the camera should be manually adjusted. Contrast levels for delaminations are small, typically ~1-2° F or less. As such, span settings in the range of 4 to 8°F are recommended for applications where solar loading is not applied. For solar loaded areas, a span of up to ~10°F may be warranted, but consideration should be given to the associated loss in sensitivity to thermal contrast in the image. The level setting should be adjusted to allow for images to be properly interpreted based on the span. This may require frequent adjustment when temperatures vary across a structure.

4.3 Angle of Observation: Observing surfaces at a low angle can increase ambient reflections and frequently produces an apparent thermal gradient across the image. Inspections should be conducted as close to normal angles (90°) as practical. A practical guideline is to try to stay within +/- 45 degrees from normal. Angles of more than 60° from normal should be avoided. Utilization of a wide angle lens can assist in maintaining normal angles when deck inspections are being conducted. Figure A1 below shows the indicated angles for reference.

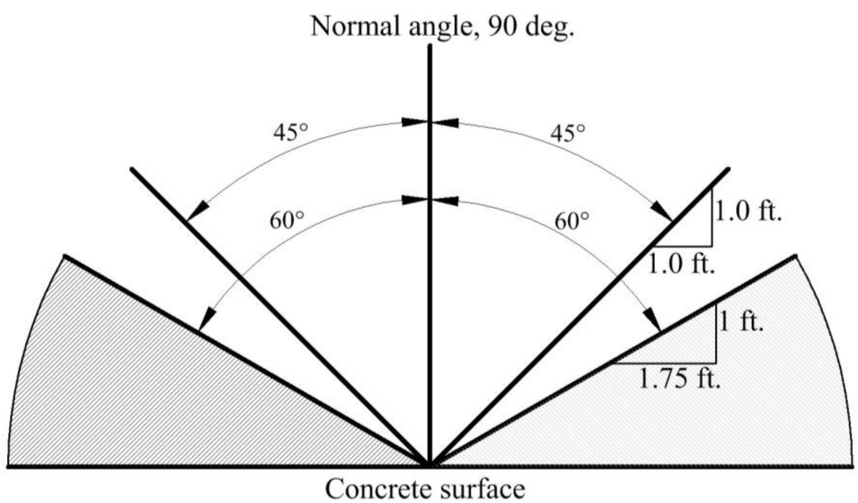

Figure A1. Schematic diagram of observation angles.

4.4 Lens Selection: Lens selection is based on the inspectors distance from the surface being inspected, assuming a critical dimension of 6 inches for the damage to be identified. If closer than 35 feet to the delamination, the wide angle lens (45°) is suggested. If further than 35 feet, the regular lens (25°) is suggested. For distance greater than 65 ft., a telephoto lens may be used.

5.0 Commentary

5.1 Wind Speed for Sunny Conditions: High wind speeds are detrimental to thermographic inspection under conditions where radiant heating from the sun is involved. Wind speed guidelines have been configured to match NWS data, based on averages provided on an hourly basis. These data were determined by correlating 6 hour averages of the second and third quarters of the day, used in the original research, with wind data provided by the National Weather Service (NWS).

5.2 Inspection time periods are based on observations in the research conducted. For solar exposed surface, measurements were made during the months of November, December and January, when there are fewer hours of sunlight than other times of the year. For shaded surfaces, measurements were made during the months of May, June and July, when there are more hours of sunlight than other times of the year. As a result, the inspection intervals suggested are for general guidance; the time of year in which the inspection is actually conducted should be considered in applying this guidance. Figure A2 can be used to estimate the inspection time periods, based on a delamination depth of 2 in. below the surface. To utilize this graph, the length of the day (sunrise to sunset) (horizontal axis) can be used to estimate the length of the inspection window on the vertical axis.

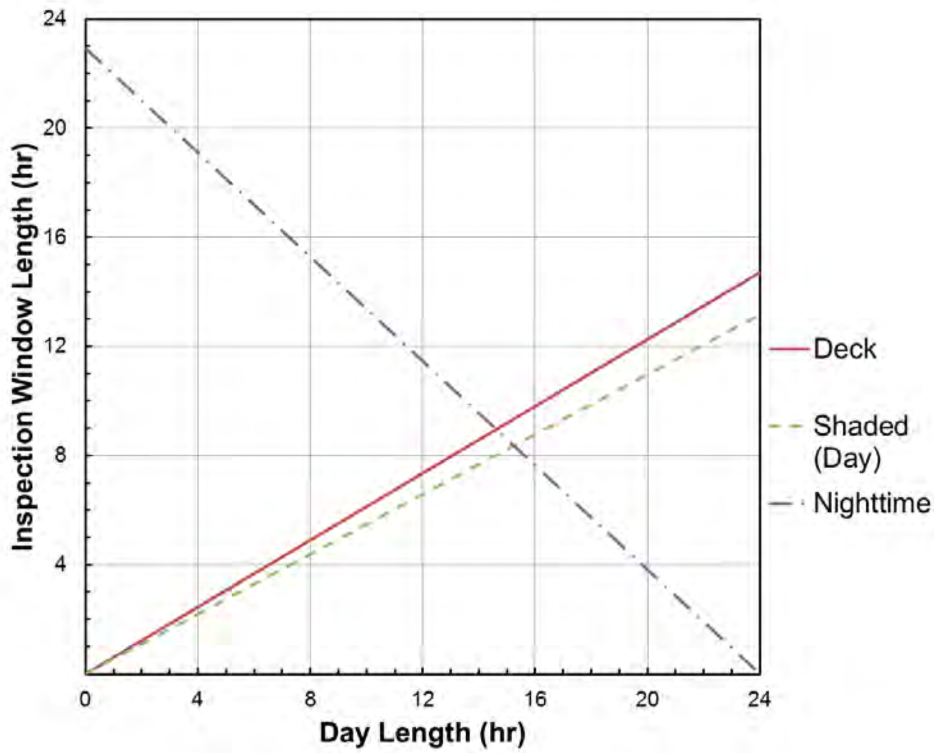

Figure A2. Graph showing inspection windows as a function of day length.

5.3 Effect of material in the delamination: If the void is filled with ice, water or epoxy, the increased thermal conductivity across the void will diminish the thermal contrast between the void and the surrounding intact concrete. Under such conditions, the subsurface void may not be detectable.

5.4 Moisture on the surface of the concrete as a result of precipitation may diminish the thermal contrast between voided areas and intact areas of concrete, due to evaporation.

5.5 Figure A3 shows the critical dimension as a function of distance for a wide angle, standard and telephoto lens. These data are based on criteria for identification of a delamination appearing as a thermal contrast in an image. Identification is based on an object occupying at least 12 pixels across its smallest dimension which was taken from Johnson's criteria for image forming systems. Based on these data, it is suggested that a wide-angle lens is suitable for inspections conducted from a distance of 35 ft. or less, a standard lens is suitable at distances of up to 65 feet, and a telephoto lens is suitable at distances greater than 65 ft.

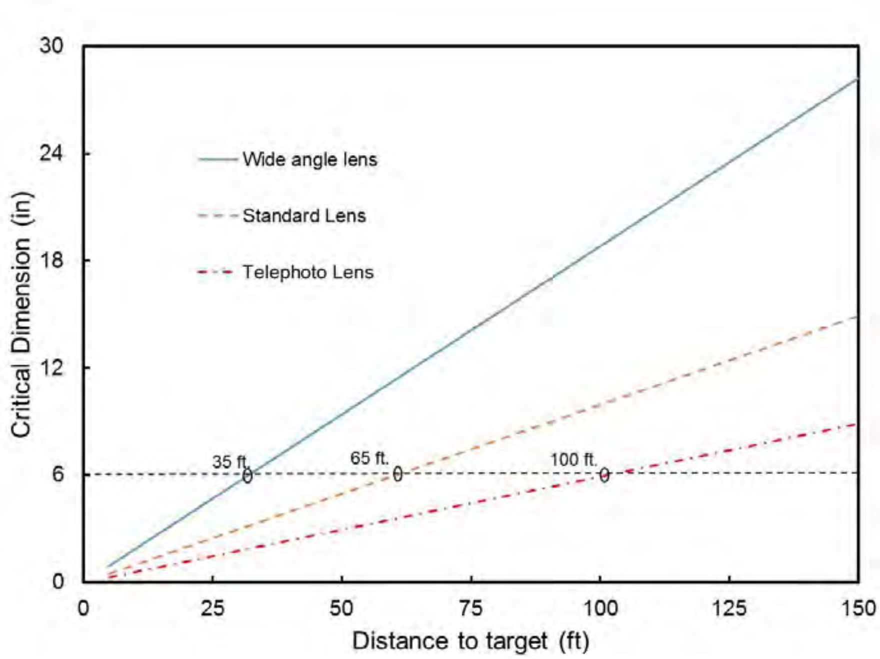

Figure A3. Graph showing critical dimension as a function of distance.

Appendix B

Examples from the Shared Data Site

University of Missouri
Columbia, MO
2014

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1 INTRODUCTION

This appendix presents images from the share data site (SDS) contributed by state departments of transportation participating in pooled fund TPF-5(247), Development of Hand-Held Thermography, Phase II. This appendix provides typical examples collected from the SDS between 2012 and 2014. The objective of this appendix is to illustrate contributions from the participants and some of the typical content of the SDS.

Each example includes a standard thermal image and a corresponding photograph. In most cases, both images are provided by the FLIR T620 camera used in the research. The corresponding ambient weather conditions of air temperature and wind speed are shown graphically. The temperature and wind data shown are those preceding the image capture, such that the time of image capture is at or near the right vertical axis of the graph. Abbreviated data from the submission, such as a location and date of the testing, are also shown.

Florida

Location: St. Petersburg

Bridge Name: Sunshine Skyway Bridge

Date and Time of Inspection: April 30, 2014 11:00am

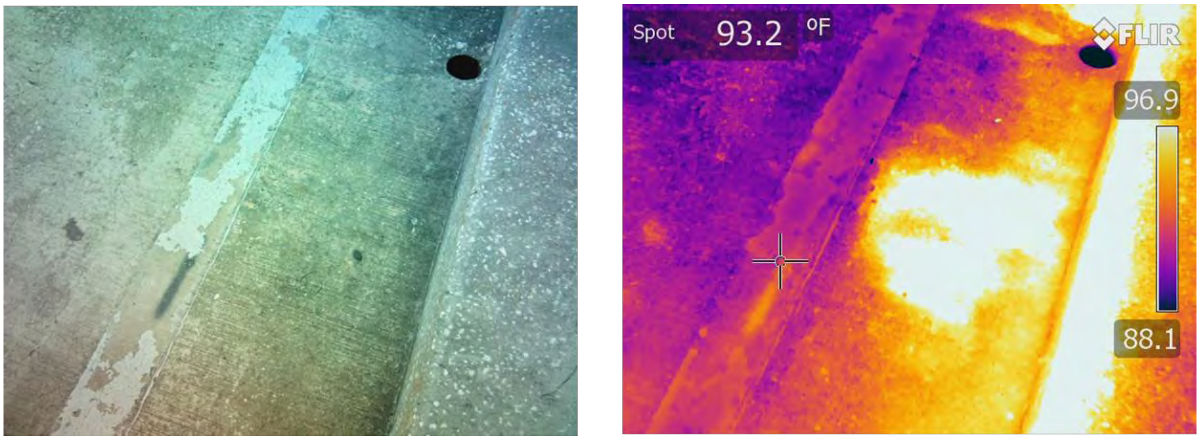

Figure 1: Standard and IR photos of bridge deck delamination (St. Petersburg, Florida)

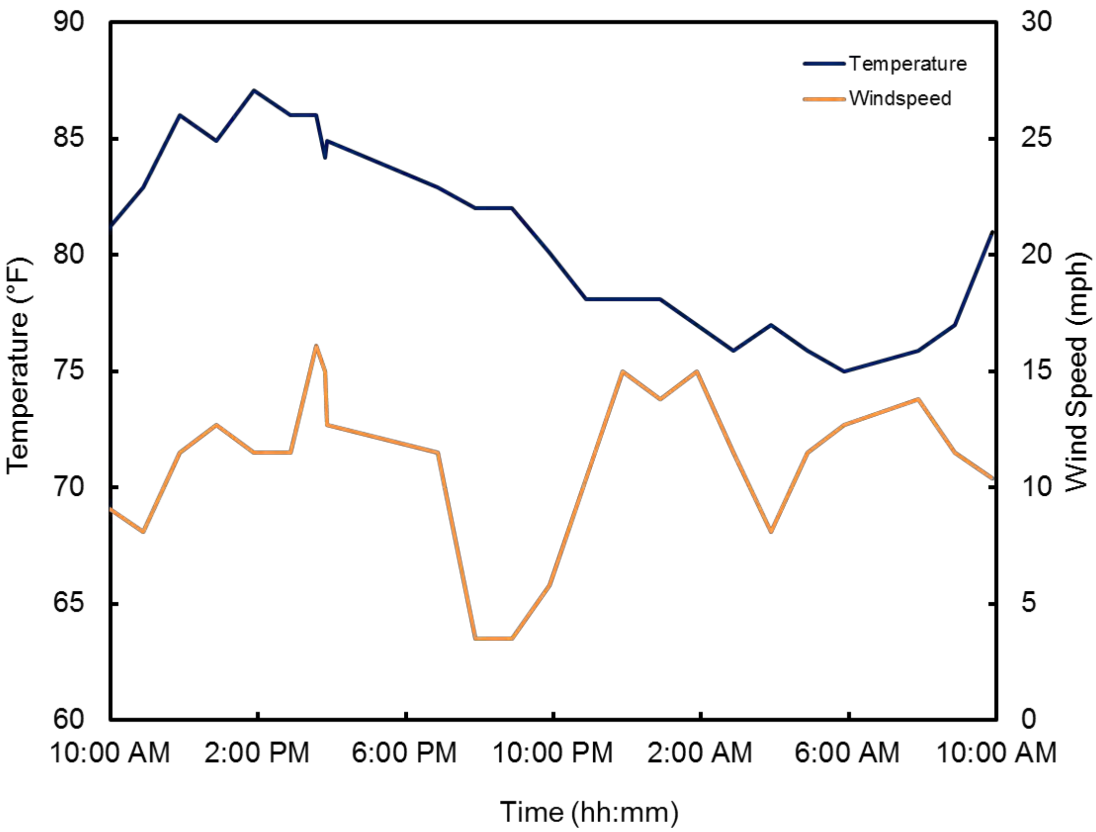

Figure 2: Weather data for the 24 hour period preceding IR inspection in St. Petersburg, Florida

Georgia

Location: Barnesville

Bridge ID: 207-0060-0

Date and Time of Inspection: May 28, 2014 3:00pm

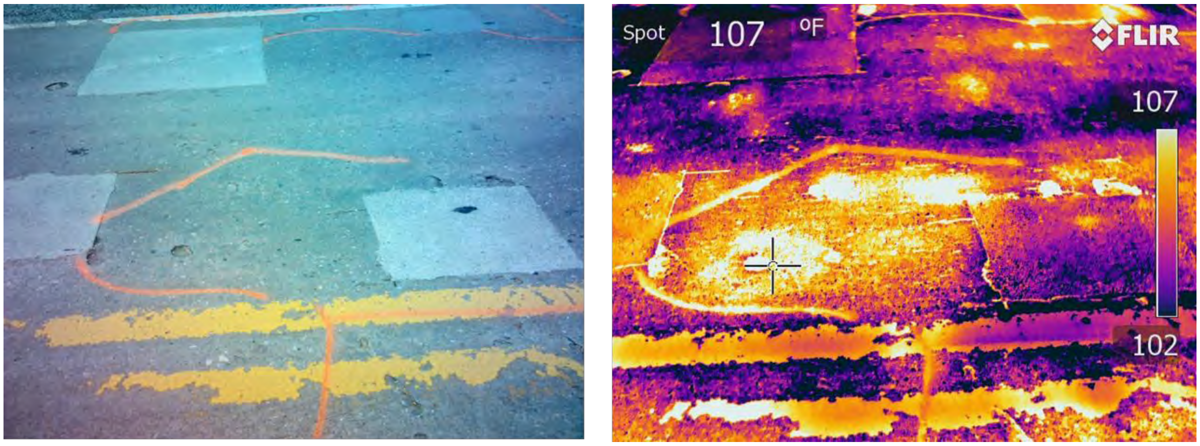

Figure 3: Standard and IR photos of bridge deck delamination (Barnesville, Georgia)

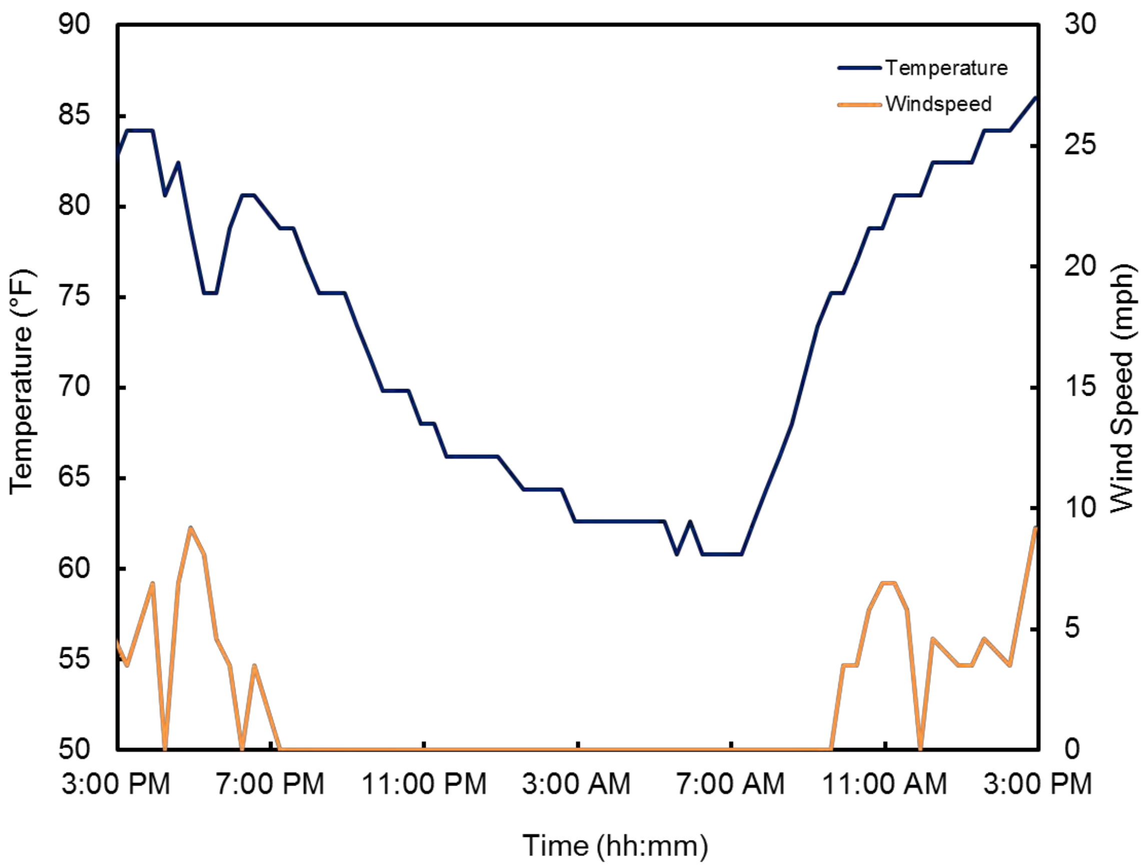

Figure 4: Weather data for the 24 hour period preceding IR inspection in Barnesville, Georgia

Iowa

Location: Vinton

Bridge ID: 14340

Date and Time of Inspection: November 28, 2012 1:00pm

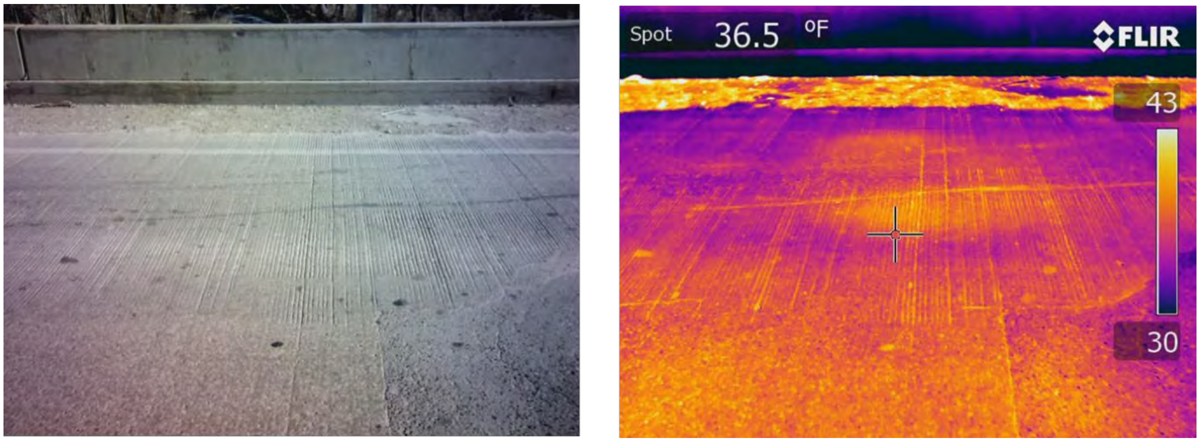

Figure 5: Standard and IR photos of bridge deck delamination (Vinton, Iowa)

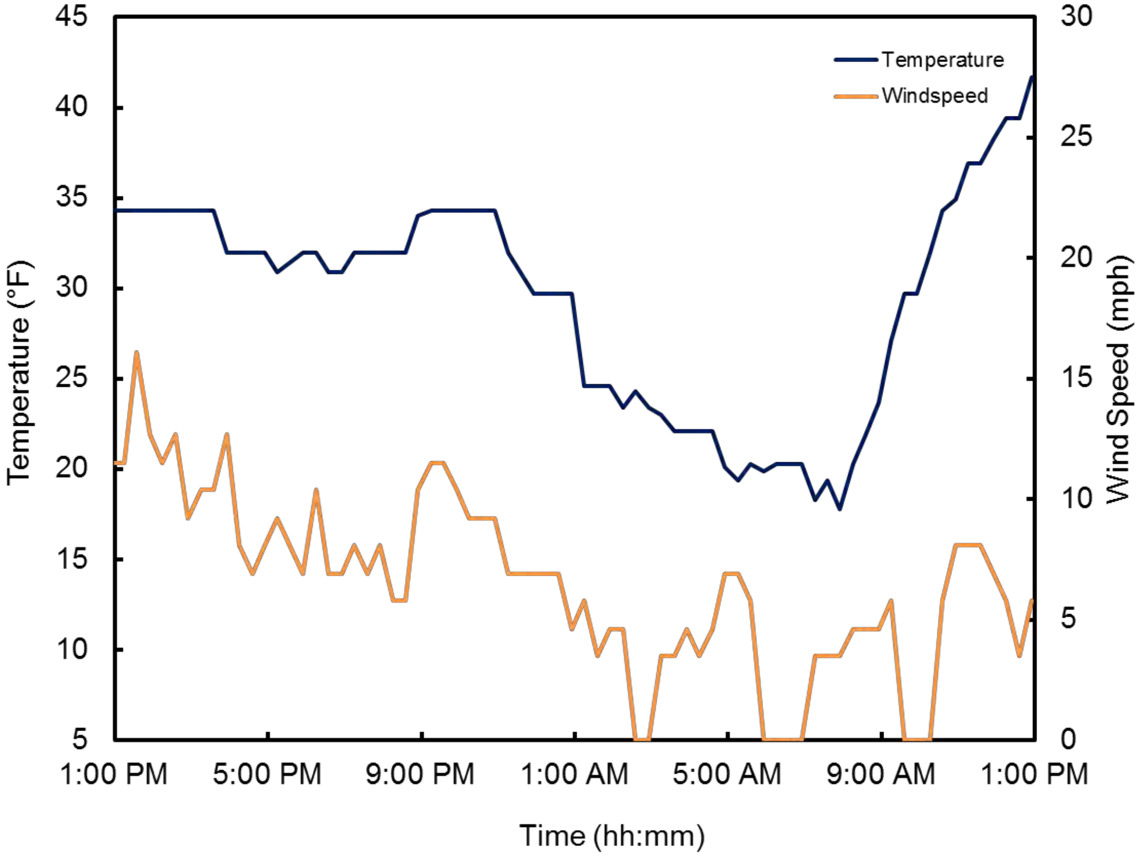

Figure 6: Weather data for the 24 hour period preceding IR inspection in Vinton, Iowa

Kentucky

Location: Mount Sterling

Bridge ID: B00060

Date and Time of Inspection: October 8, 2013 5:00pm

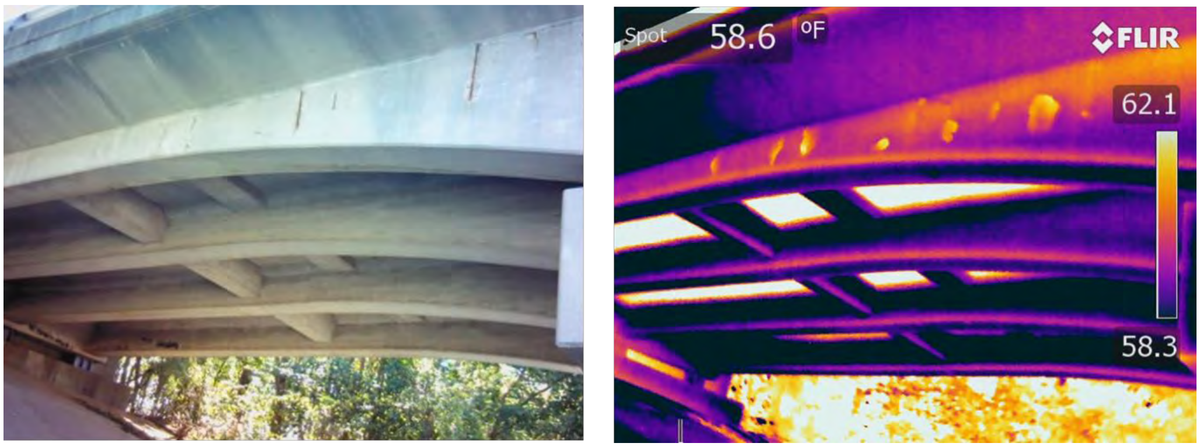

Figure 7: Standard and IR photos of bridge soffit delaminations (Mount Sterling, Kentucky)

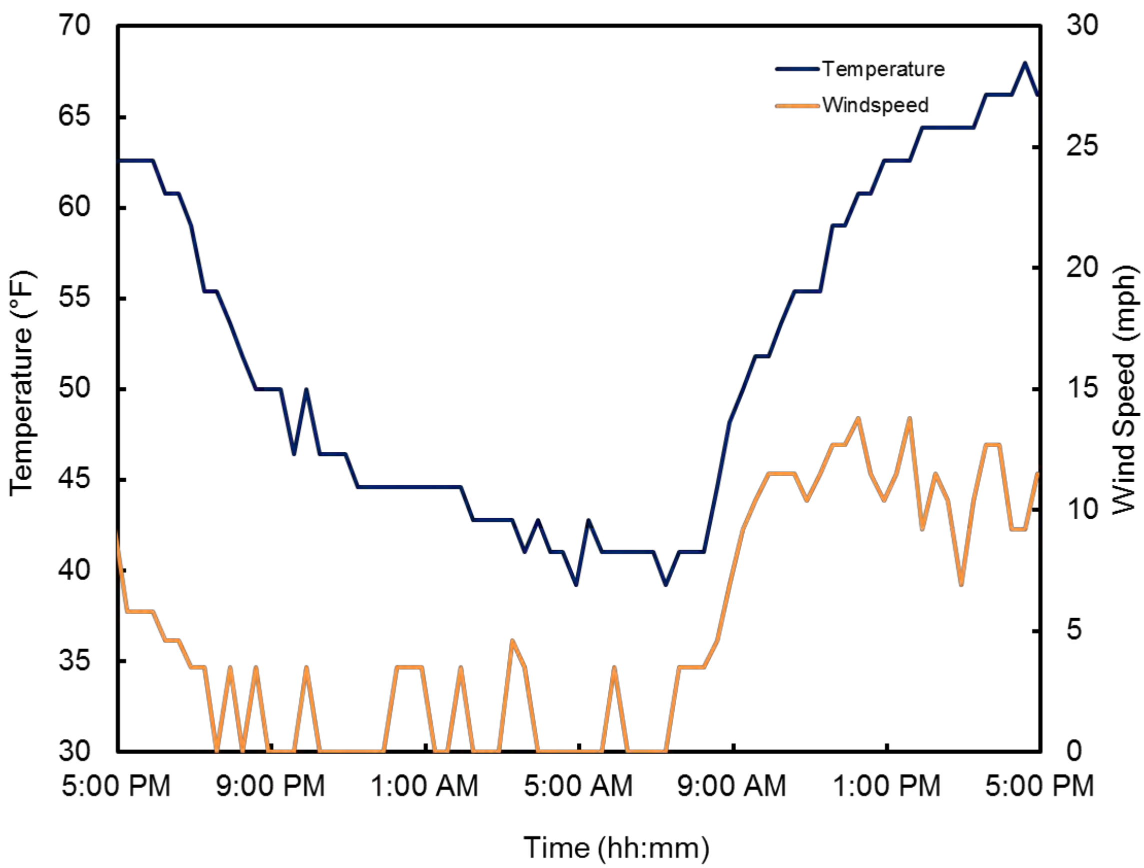

Figure 8: Weather data for the 24 hour period preceding IR inspection in Mount Sterling, Kentucky

Minnesota

Location: Duluth

Bridge ID: 69802C

Date and Time of Inspection: August 6, 2012 8:30am

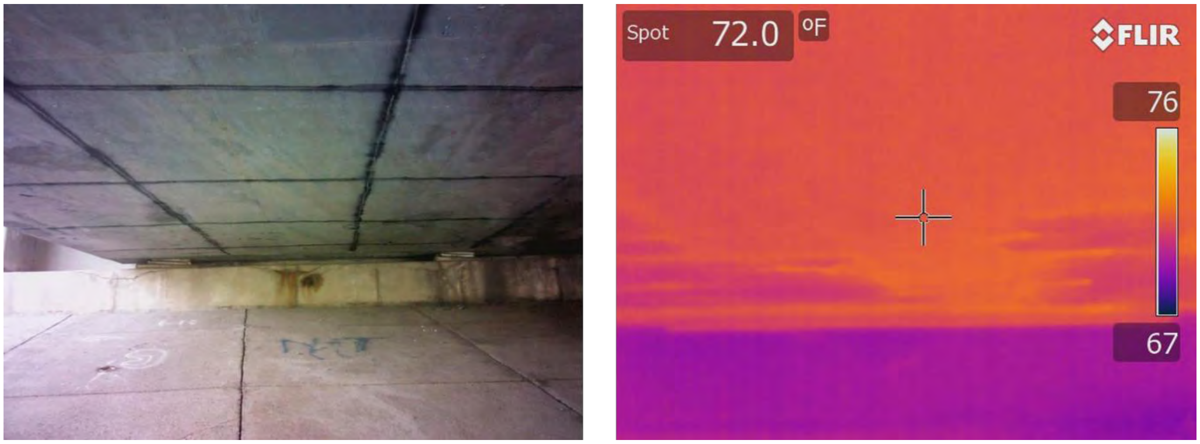

Figure 9: Standard and IR photos of bridge soffit delaminations (Duluth, Minnesota)

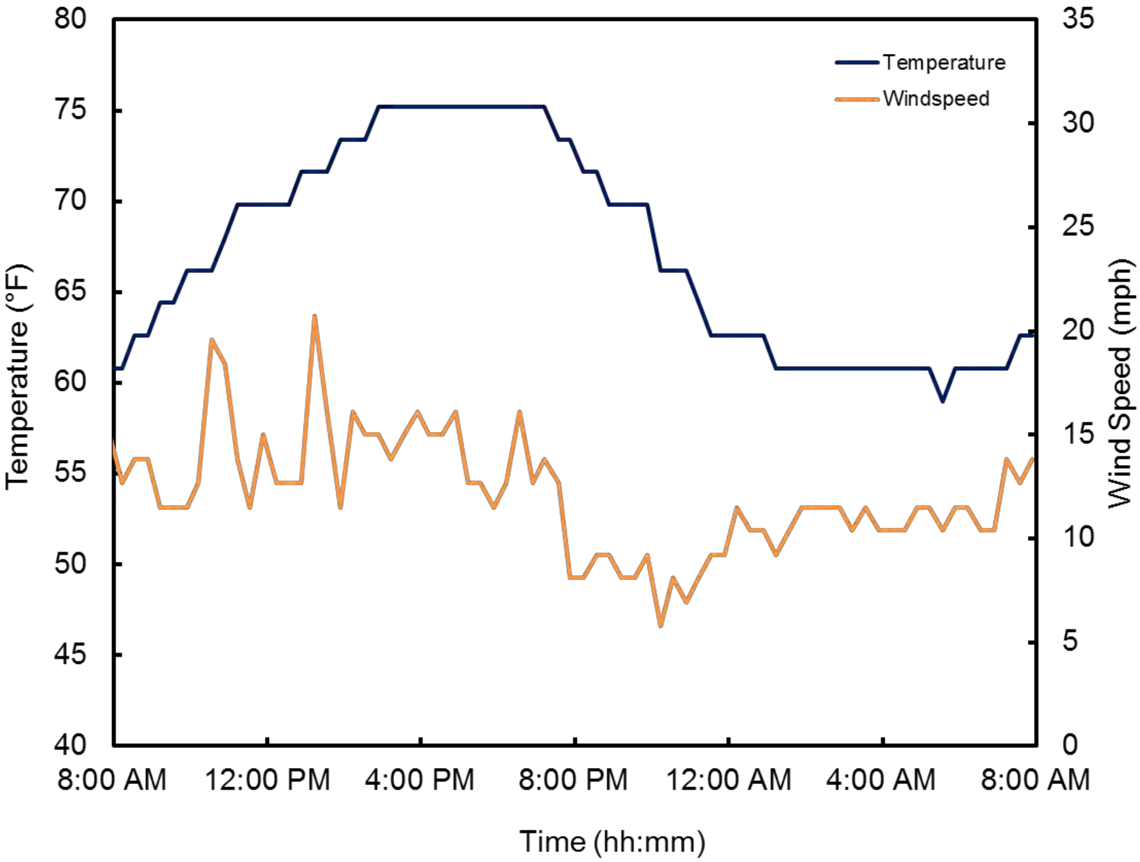

Figure 10: Weather data for the 24 hour period preceding IR inspection in Duluth, Minnesota

New York

Location: Albany

Bridge ID: 1033142

Date and Time of Inspection: November 20, 2013 11:30am

Figure 11: Standard and IR photos of bridge substructure delaminations (Albany, New York)

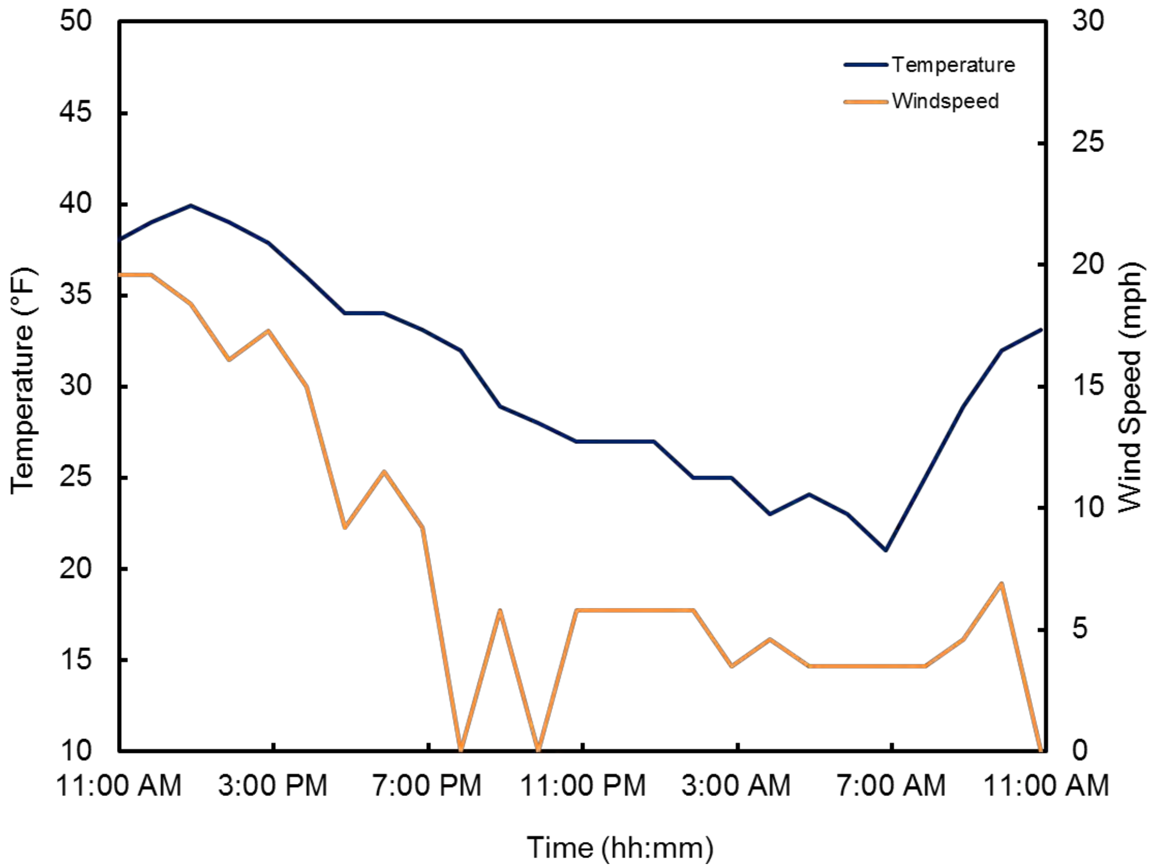

Figure 12: Weather data for the 24 hour period preceding IR inspection in Albany, New York

Ohio

Location: Harveysburg

Bridge ID: PRE-726-0428

Date and Time of Inspection: October 9, 2013 12:17pm

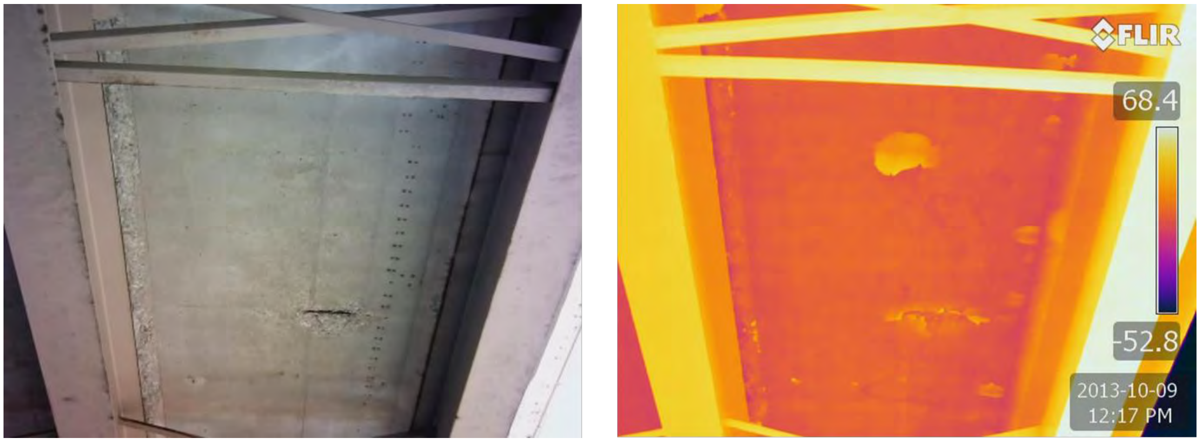

Figure 13: Standard and IR photos of bridge substructure delaminations (Harveysburg, Ohio)

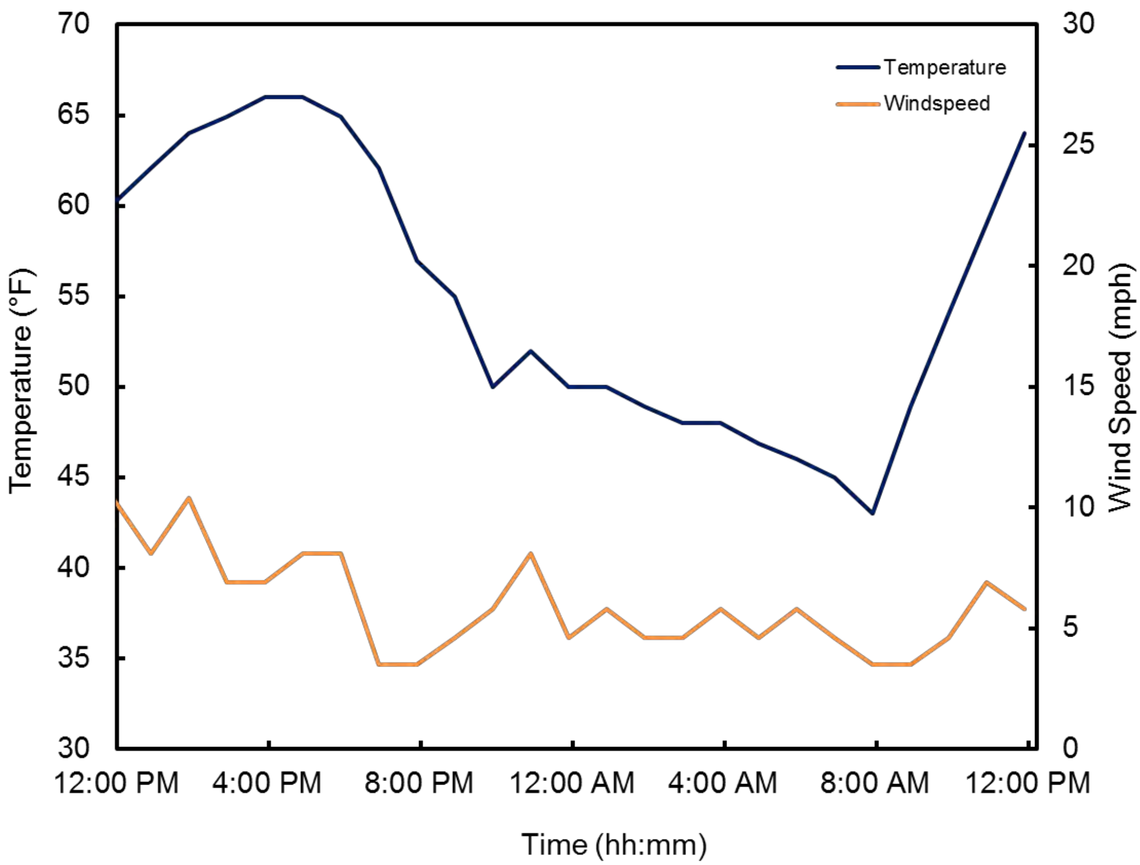

Figure 14: Weather data for the 24 hour period preceding IR inspection in Harveysburg, Ohio

Oregon

Location: Woodburn

Bridge ID: 07801A

Date and Time of Inspection: August 8, 2013 2:30pm

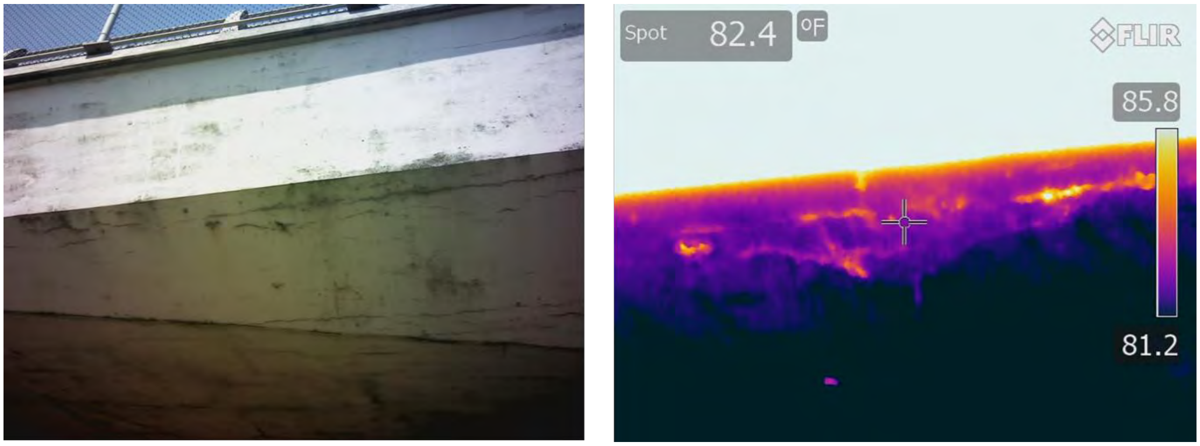

Figure 15: Standard and IR photos of bridge soffit delamination (Woodburn, Oregon)

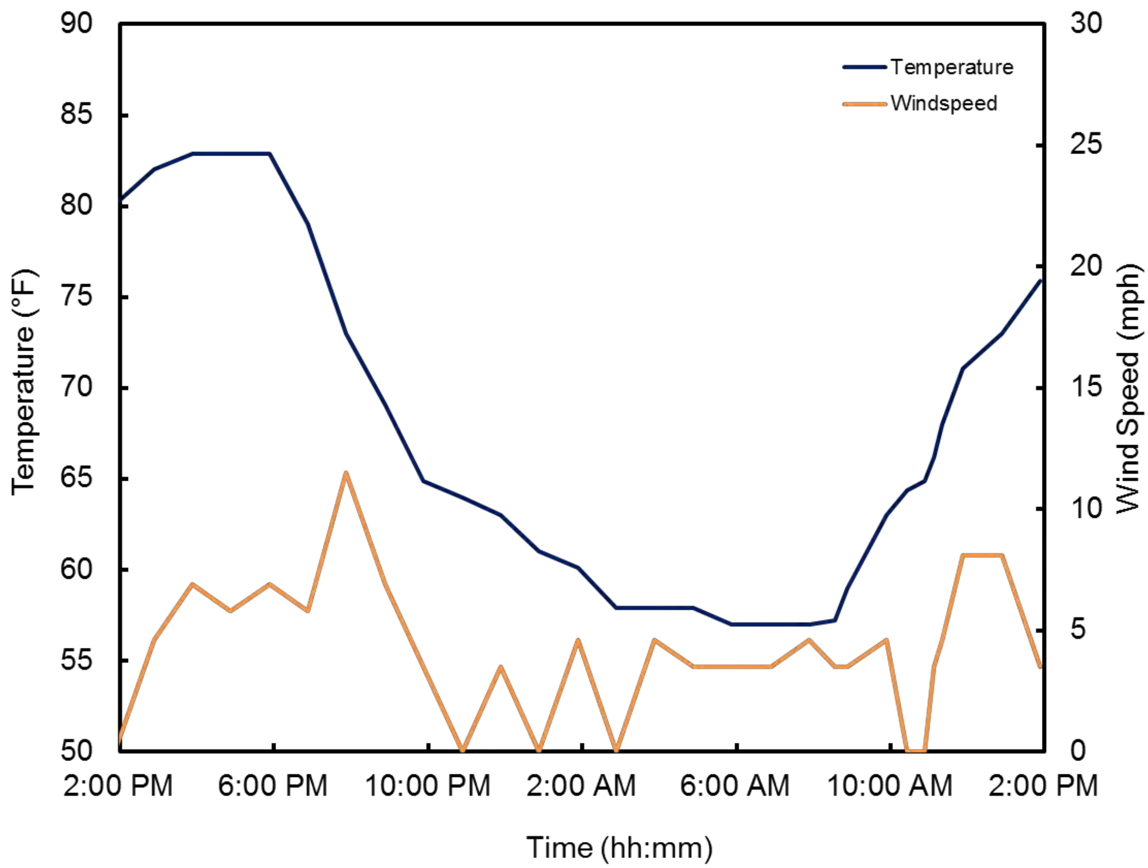

Figure 16: Weather data for the 24 hour period preceding IR inspection in Woodburn, Oregon

Texas

Location: Waco

Bridge Identifier: IH 35

Date and Time of Inspection: May 22, 2014 7:25pm

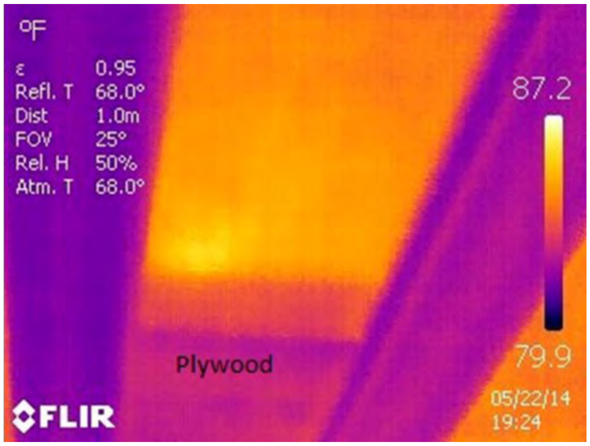

Figure 17: Standard and IR photos of bridge soffit (Waco, Texas)

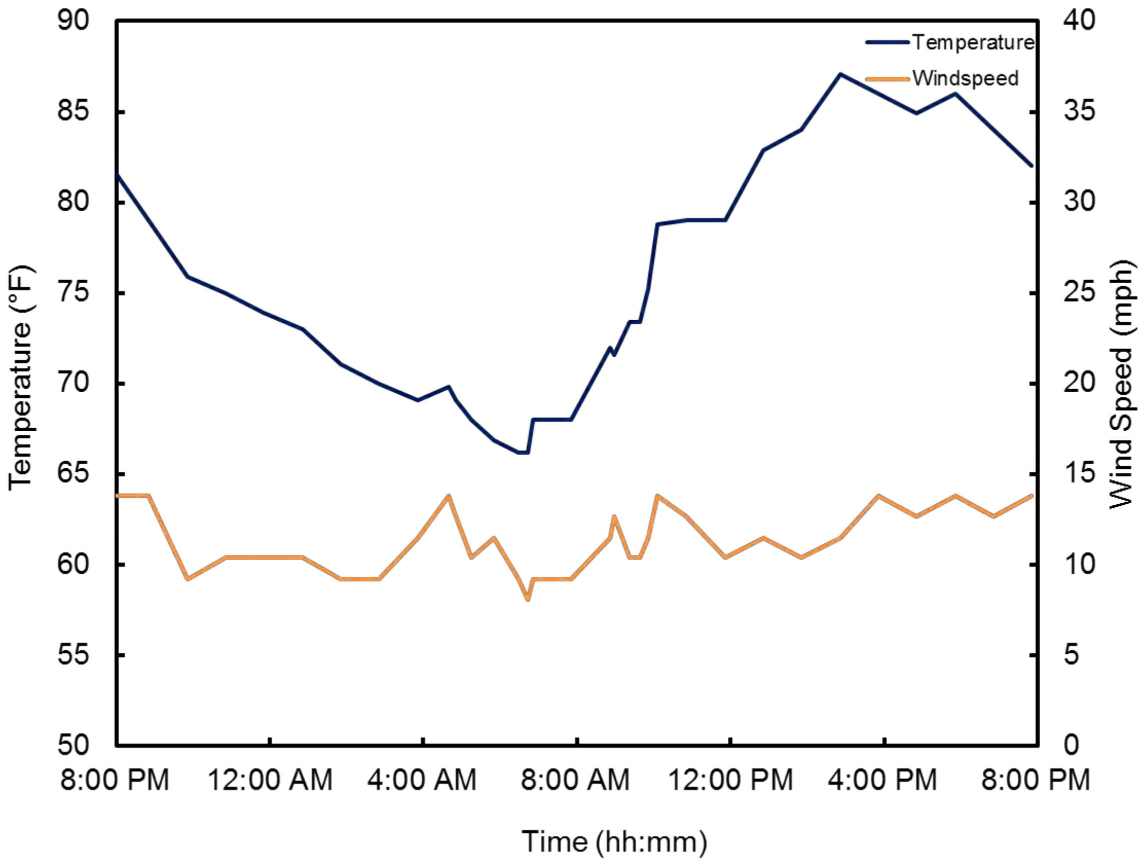

Figure 18: Weather data for the 24 hour period preceding IR inspection in Waco, Texas

Wisconsin

Location: Richland Center

Bridge ID: B520008

Date and Time of Inspection: April 3, 2013 2:00pm

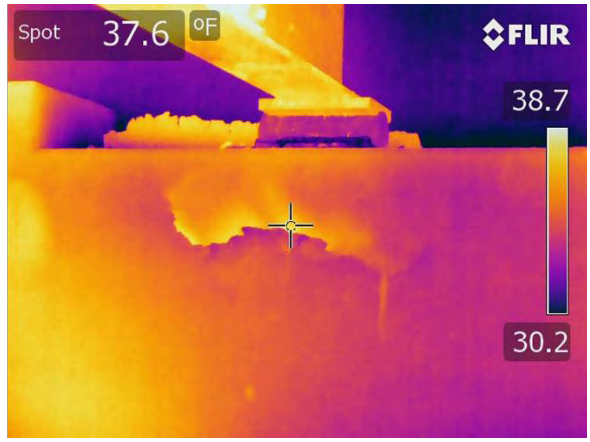

Figure 19: Standard and IR photos of bridge support delamination (Richland Center, Wisconsin)

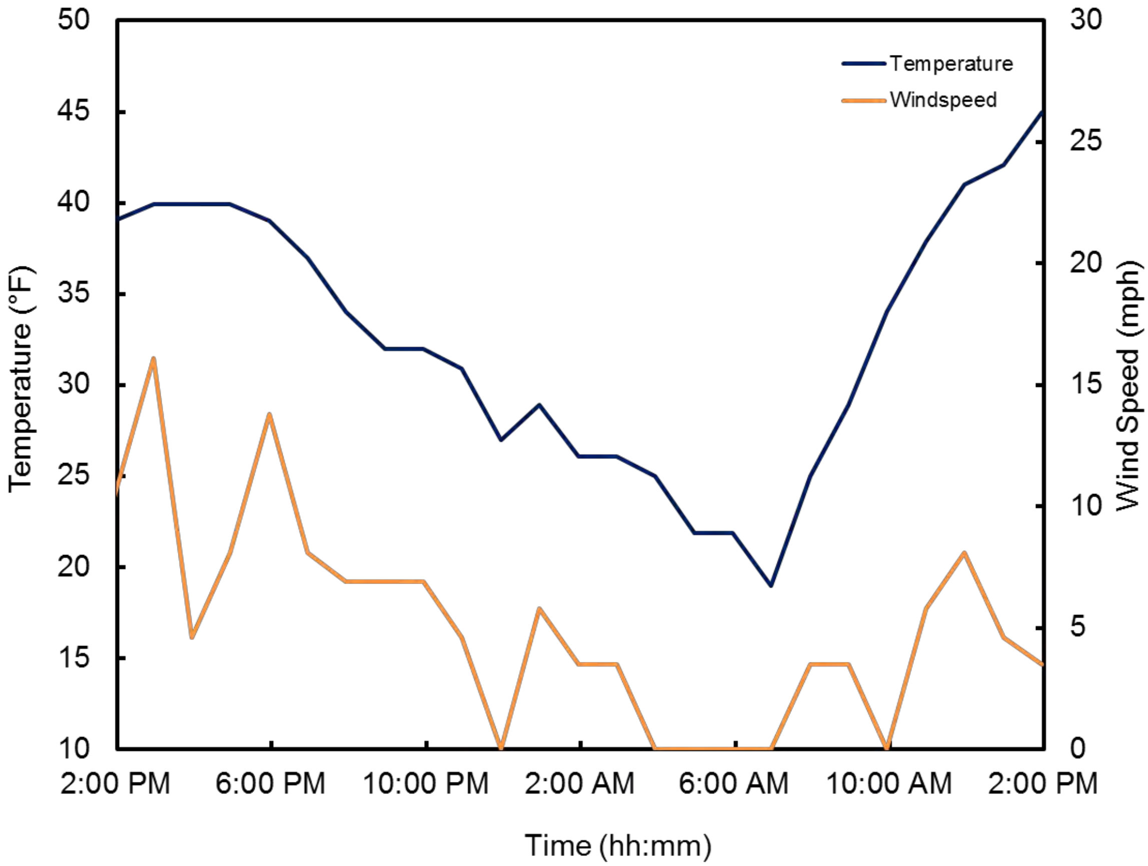

Figure 20: Weather data for the 24 hr period preceding inspection in Richland Center, Wisconsin

Oregon

Location: Astoria

Bridge ID: 00711

Date and Time of Inspection: July 12, 2012, 11:20 AM

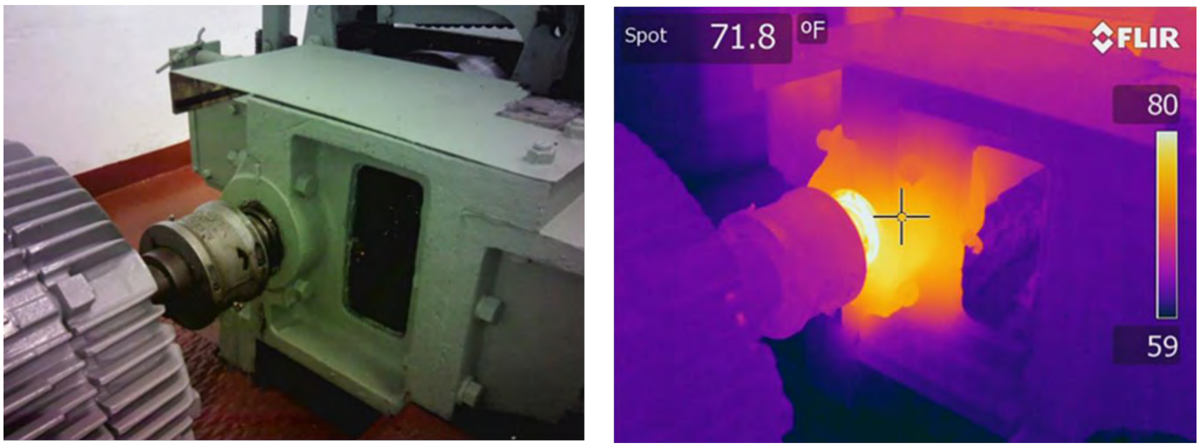

Figure 21: Standard and IR photos of Lewis and Clark River drawbridge mechanism (Astoria, Oregon)

Weather data: not relevant

Verification Testing Summary Report

Appendix C

University of Missouri

Columbia, MO

February, 2014

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INTRODUCTION

Phase II of the Infrared Thermography pooled fund project includes verification testing in the 13 participating states. This appendix summarizes highlights from the verification testing conducted as a part of the project. The dates of verification, weather data and thermal images are included in each state's section of the report. To date, verification trips have been made to ten of the thirteen participating states: Missouri, Minnesota, Iowa, Georgia, Wisconsin, Pennsylvania, Texas, Oregon, Kentucky, New York and Ohio. Of these, Texas and Wisconsin were unsuccessful trips due to weather conditions. The two remaining states are Michigan and Florida. Future verification using the Infrared Ultra Time Domain (IR-UTD) system will be provided in Volume B of the verification report.

GOALS AND OBJECTIVES

The objective of the verification testing is to verify thermal imaging results of bridge components with other known assessment methods. These other assessments could include coring, hammer sounding or the use of a borescope. The reason for coring and the use of the borescope was to observe a physical depth of delaminations. Sounding was utilized to determine the spatial extent of a delamination. A combination of the methods provides an accurate assessment for the delamination as a whole in regards to size and depth. In most cases, verification testing was completed by comparing IR results with sounding or chain drag results.

In summary, the results of the verification testing indicated that infrared imaging was a reliable technology when the weather conditions described in the Guidelines were present, and the depth of the damage to be detected was 3 in. or less. When the weather conditions were not as described in the Guidelines, thermal imaging was generally ineffective. There was a single case where a delamination in the bridge pier, identified using sounding, was not identified using infrared thermography in the field. For a case where the substructure was exposed to direct solar loading over portions of the substructure, thermal gradients resulting from the solar exposure made thermal imaging very difficult. This appendix is provided to present an overview of the verification testing conducted as part of the research.

1 MISSOURI

1.1 Kansas City

Testing in Missouri is ideal due to the close proximity to the University of Missouri. Bridge A0295 in Kansas City was originally constructed in 1959 and never opened to traffic due to a change in the original plans. The result of no traffic volume on the bridge was that salt was never applied to the roadway. This bridge was selected for research since it would provide a good baseline for the performance of similar bridge decks in the area; also, researchers hoped to demonstrate the impact of salt on the amount of delamination on a deck.

The verification testing was completed on this bridge on March 9th, 2014. Thermal images were captured over the entire bridge deck. However, results for only a single span are presented herein. For other portions of the bridge, results were consistent with the span presented.

Testing on this bridge was conducted to compare results achieved with the infrared camera to chain drag results. An infrared camera located and captured the delaminations. Chain dragging was performed by the Missouri Department of Transportation to verify the infrared results. Each delamination identified with the infrared camera was verified by the results of the chain dragging. The results of the hammer sounding are shown in Figure 1 below. Figures 2 and 3 show infrared images of these delaminations.

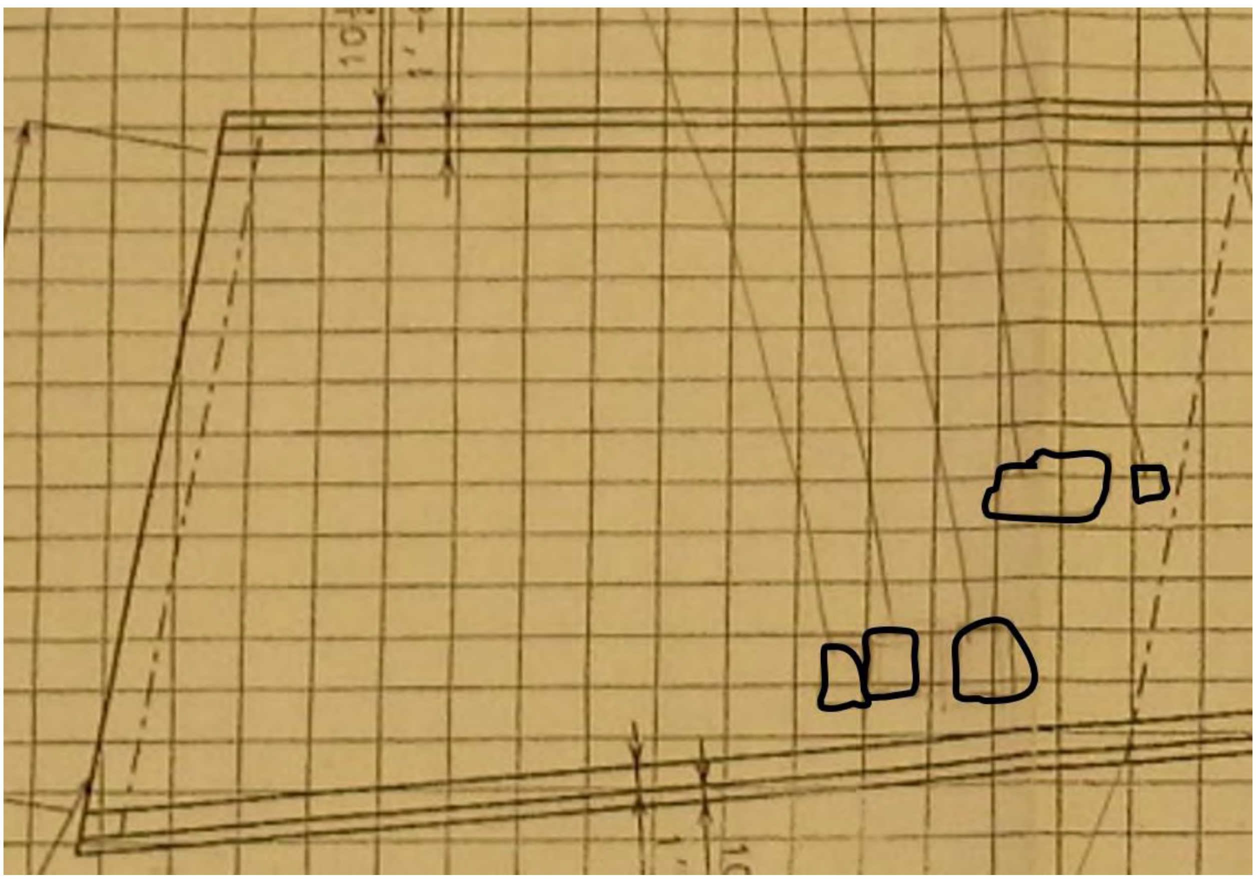


Figure 1: Chain drag results for the North span of Bridge A0295

The delamination edges for one delamination were sounded as objectively as possible and compared to the infrared images. The accuracy of the infrared images is shown in Figure 2 below. The hammer sounding results are shown in the digital image as a red outline.

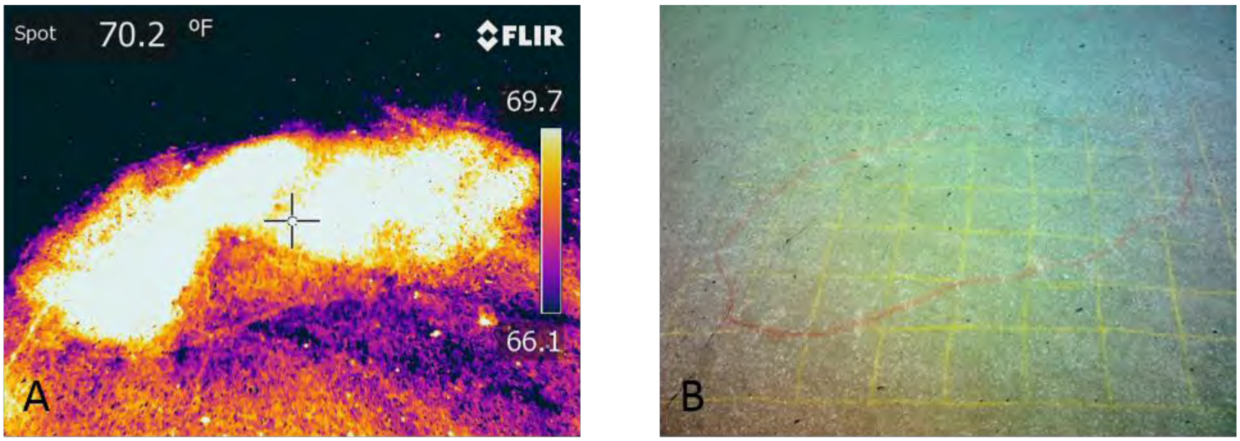


Figure 2: Infrared (A) and digital (B) images of a deck delamination in Kansas City

The two images demonstrate that the accuracy of the handheld infrared camera is very high. The red outline marking can be seen in the infrared image indicating how accurate the infrared camera and the hammer sounding results really were. Another group of delaminations are shown in Figure 3.

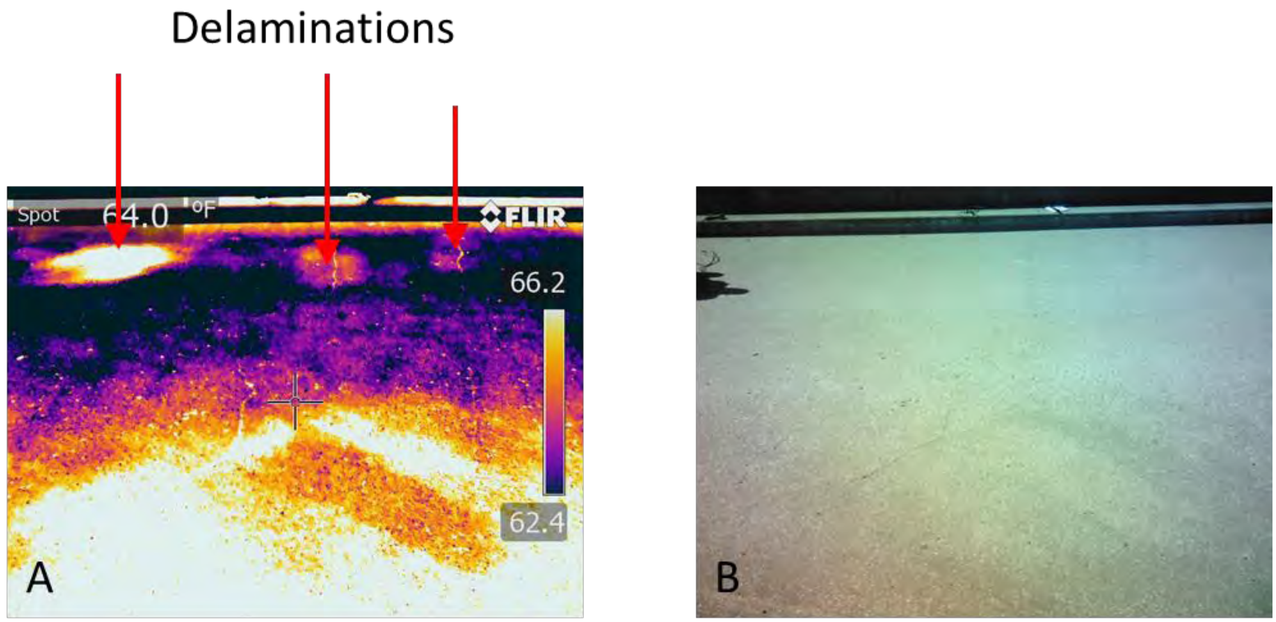


Figure 3: Infrared (A) and Digital (B) images of a group of delaminations in Kansas City

The weather conditions for the day were very positive for infrared thermography. The ambient temperature change was approximately 37 degrees over the span of the day with a change of 27 degrees in the first six hours after sunrise. The wind speed got to 21.9 miles per hour which is above the desired threshold for inspection (15 mph); however, with such a dramatic change in ambient temperature, the high wind speeds were not enough to be detrimental to inspection. The ambient temperature data for the day can be seen in Figure 4 below.

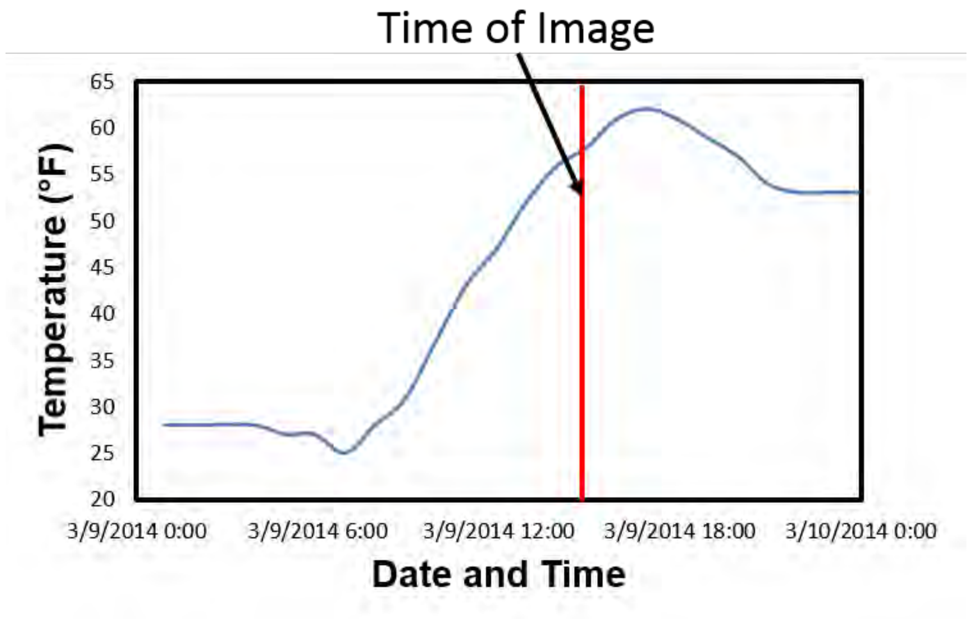


Figure 4: Ambient Temperature for Kansas City, MO on March 9th, 2014

1.2 Providence Road

The Providence Road Bridge over Hinkson Creek in Columbia was tested on May 6th, 2014. The testing was conducted on the northbound lanes of Providence Road. Testing on this bridge was utilized because of the close proximity to the University of Missouri. Images were taken on the deck and soffit of the bridge. Soffit images are shown on the pooled fund website. Delaminations in the deck are shown as "hot spots" in Figure 5.

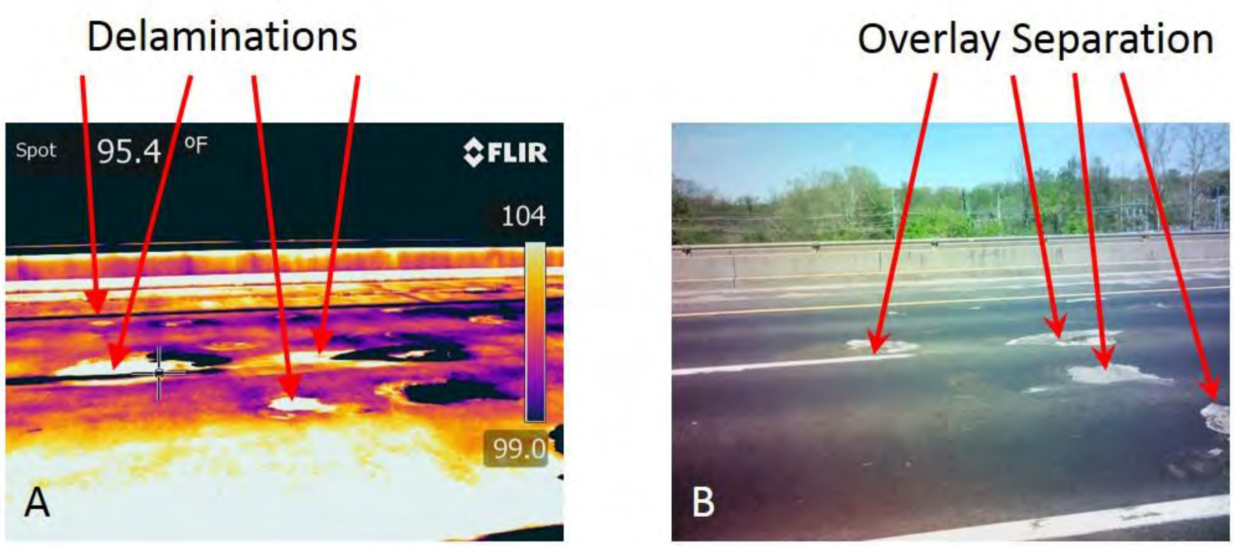


Figure 5: Infrared (A) and Digital (B) images of Providence Rd. Bridge (northbound) over Hinkson Creek

It is often the case that delaminations form near the edges of patches and separations in overlays. The reason for this occurrence is due to the fact that not all of the original damage was repaired. Cracks left unrepaired near the edge of a patch will continue to propagate and lead to more delamination.

The conditions were excellent for inspection with infrared thermography. The ambient air temperature for the day of the test can be seen in Figure 6 below. As shown in the figure, the ambient temperature change is approximately 32 degrees with 23 degrees of change in the first six hours after sunrise. The wind speed reached approximately 22 mph. With a smaller ambient temperature difference, a 22 mph wind speed would be detrimental to inspection. In this case, the amount of change in ambient temperature was sufficient to negate the effects of cooling by the wind.

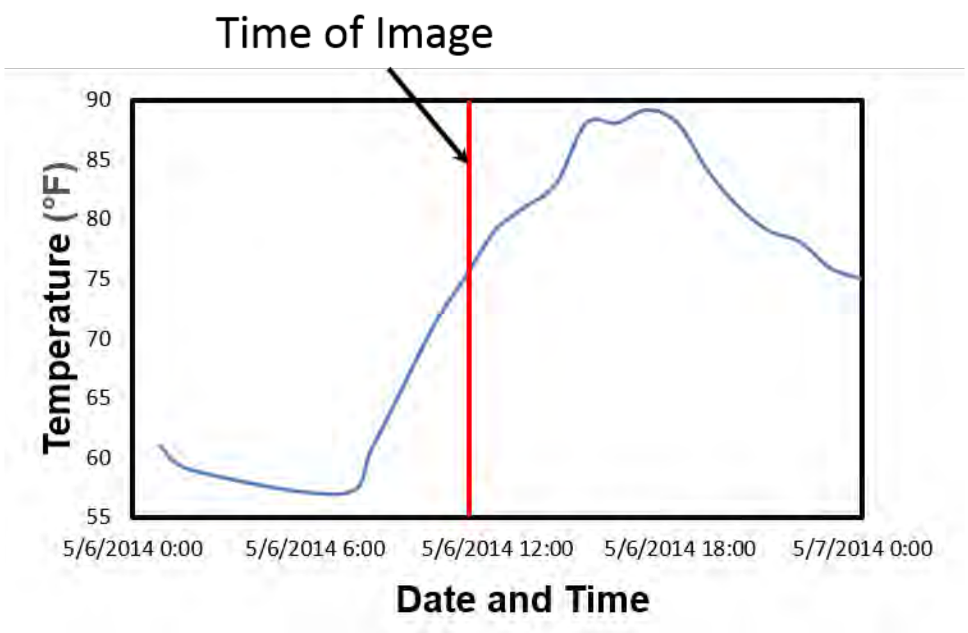


Figure 6: Ambient temperature on May 6th, 2014 for Columbia, MO

2 MINNESOTA

2.1 Trip 1 Results and Analysis

The objective of the first day of the verification trip was to verify delaminations in Bridge 85006 which had been inspected with IR during a previous training trip. MNDOT inspectors marked out the bridge using a chain dragging approach so as to verify the effectiveness of the IR to find the delaminations. The IR camera showed the defects as smaller than the areas chain dragged by the MNDOT inspectors. The edges of the sounding result were inaccurate due to multiple points of contact by the sounding device. Not all points of contact were necessarily sounding delaminated areas near the edges but there is no way of telling how many were. The result of this sounding method is an over estimation of total delaminated area. Figure 7 is an image of the chain drag tool used for inspection. Figure 8 shows the chain dragging results marked out in white paint in image A and the IR results in image B.

Figure 7: Chain drag used by MNDOT inspectors

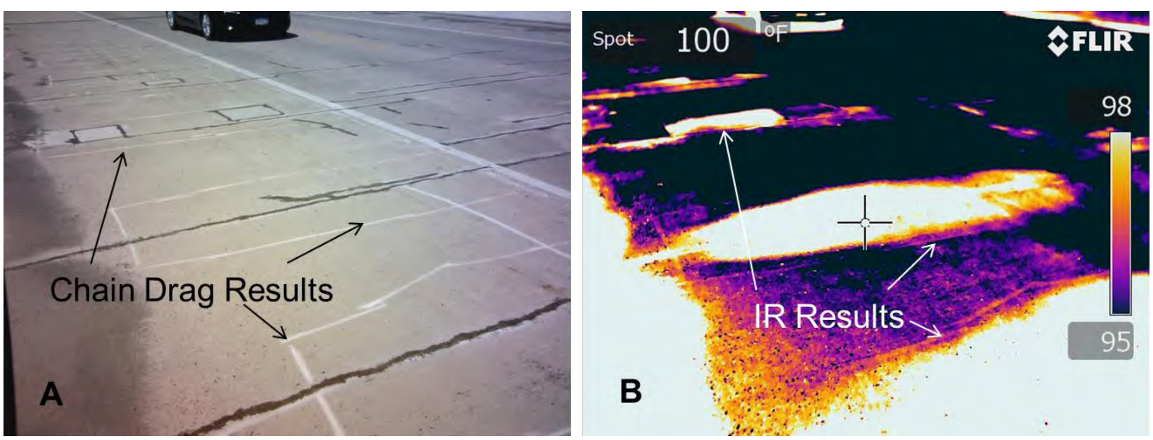


Figure 8: Chain dragging (A) and IR (B) results of deck delaminations.

To verify that the actual size and shape of each delamination matched the IR findings, inspectors used a hammer to sound the delaminations with the goal of increasing the precision of the verification test. The hammer sounding results confirmed that the chain dragging markings were bigger than the actual delaminations and that the IR images provided a more accurate assessment.

The inspections for the next two days of the verification trip focused on the soffit area of the bridge. This was due to poor weather conditions for deck inspection. The weather was cloudy with a light rain. In addition to the rain, the temperature range for these two days was smaller than recommended for a successful IR inspection. Figure 9 shows images of a defect in the soffit area around a cross brace detected using IR. The purpose of the figure is to demonstrate imaging from a distance under less than ideal weather conditions. Image A shows a digital picture of the soffit while image B shows a delamination detected using IR that had not been visible during ground inspection. The soffit of the bridge in this area is approximately 50 feet off the ground, which would require specialized equipment to have hands-on access to test for damage if IR had not been used.

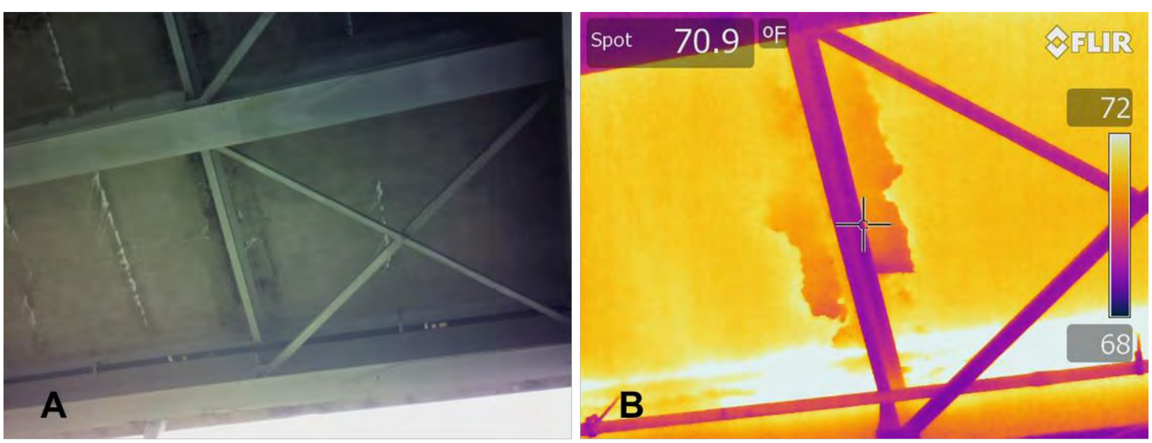


Figure 9: Delamination with some spalling by a cross brace in the soffit

2.2 Trip 2 Results and Analysis

The objective of the second verification trip to Minnesota was to remove cores on a bridge that had previously been marked out with hammer sounding/chain dragging and IR. The MNDOT inspectors determined core locations based on the areas of delamination identified by the IR cameras; this would allow the inspectors to take a closer look at those delaminations.

Multiple cores were removed from 3 different locations in the bridge deck. A total of seven cores were taken; specific drilling sites from Location 1 are shown in image A in Figure 10 and the cores themselves are displayed in Figure 11. The locations of the cores were picked because of the variation in thermal contrast in the delamination and surrounding area. The cores were taken to investigate if the changes in thermal contrast correlated to changes in depth of the defect.

Table 1 summarizes the depth of the delamination at different locations.

Table 1: Depth of cover above delaminations at different locations

MN Verification Cores			
Sample	**Location**		
	L1	**L2**	**L3**
S1	1 7/8"	2"	3/4"
S2	2 5/8"	1/2"-3/4"	2"
S3	2 3/8"	-	-

The amount of heat variation in the delaminated area was the determining factor in selecting specific core samples of the delaminations. Figure 10 shows the delamination at location 1 (L1). L1 had a small, very hot area, which is shown as white in the IR image, a large yellow area around the white, and areas of pink around the outer limits of the delaminations. For this location, three cores were taken. The first sample was taken just off the area showing up as white in image B in Figure 10. Typically, the highest thermal contrast indicates an area closest to the center of a delamination.

The second core was taken at the edge of the delamination that showed only a slight increase in the thermal contrast from the solid concrete around it. In the IR image below, the contrast between the core location and the solid concrete was less defined. This is because the difference in temperature between the average temperature of the core location and the average temperature of the solid concrete around the delamination is 0.6°F. A thermal difference of less than one degree can be difficult to detect visually on the camera screen during the time of inspection, even with a very small span; this is because of differences in emissivity, surface cracks, paint, sand, and other debris that can appear to be at a slightly different temperature than the solid concrete. This difference in temperature was believe to be caused by a subsurface defect since this area appeared to be clear of any debris and the surface color of the concrete was consistent with the majority of the bridge deck.

The third sample was taken from an area that had a distinct difference in thermal contrast from the first sample and less distinct thermal contrast than the second sample. This shows up as mostly yellow with some pink in image B below.

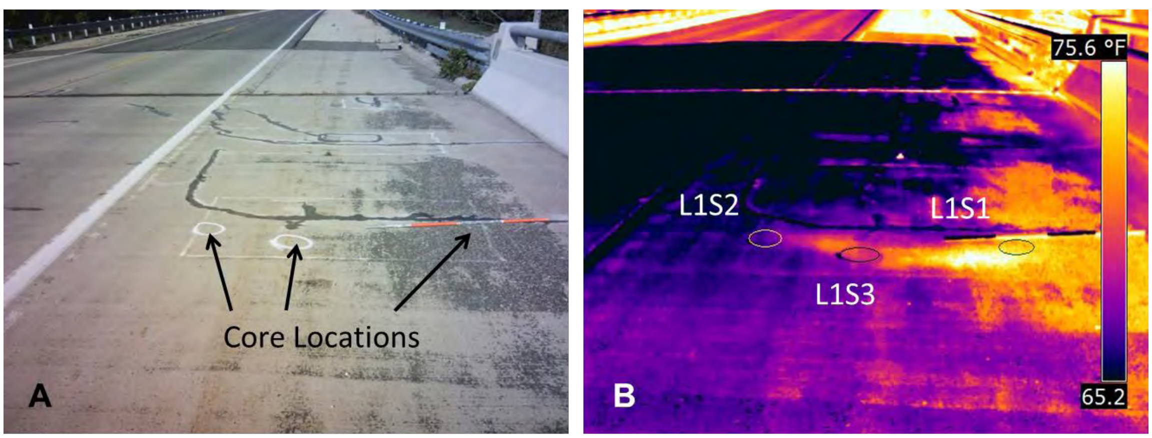


Figure 10: Cores at Location 1

These thermal differences within the same delamination were due to the variation in cover above the delamination as shown in Figure 11. Sample 1 was taken just off the area that appears white in the IR image; in this area, the delamination was the closest to the surface. Sample three had the lowest thermal contrast of the three samples and the core had the largest amount of cover above the delamination. The cover above the delamination corresponded to the thermal difference detected by the camera. The smaller the cover above the delamination, the larger the thermal difference between the defect and the surrounding sound concrete.

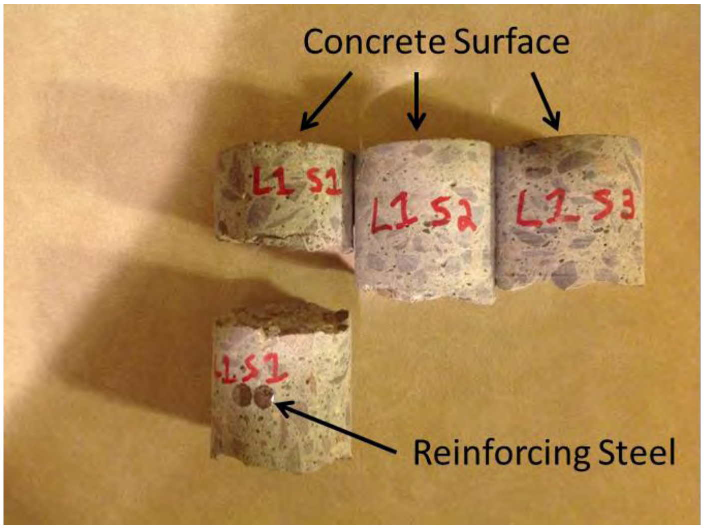


Figure 11: The cores taken from the delamination at L1

Figure 11 shows all three samples taken from location 1 and the depth of the reinforcing steel. The reinforcing steel was at a depth of approximately 3 ½" from the surface. None of the samples showed any signs of an overlay and all of the samples taken of the delamination at location 1 were well above steel. The causes of this delamination are not yet known and are still being investigated (Nelson).

2.3 Results from Training

An example of soffit imaging can be seen in Figure 12. This figure shows a thermal image of the soffit area of a bridge in the area of a longitudinal joint. A parapet on the bridge deck (not shown in the image) creates an area in the soffit where temperatures are relatively cooler, due to the shadowing effect of the parapet and its thermal mass. In deck areas adjacent to the parapet, the heating from the sun has conducted through the deck. In the figure, a delamination in the soffit area of the deck is encircled. Four temperature measurements were made in this area and are labeled A, B, C and D. These data indicated that the nominal temperature of the deck at point A was 54.8°F, while the delaminated area labeled B was 53.9°F, indicated that the delaminated area is cooler than the intact deck area, due to the conduction effect. Conversely, the delaminated area marked C displays a temperature of 50.1°F, while the delaminated area marked D 52.7°F, warmer than the surrounding concrete. This figure illustrate the conduction effect very well, because the same delamination appears both cooler than its surrounding where the conduction effect is warming the deck, and warmer than its surrounding where the parapet on the deck above is creating a shadowing effect that eliminates the conduction effect.

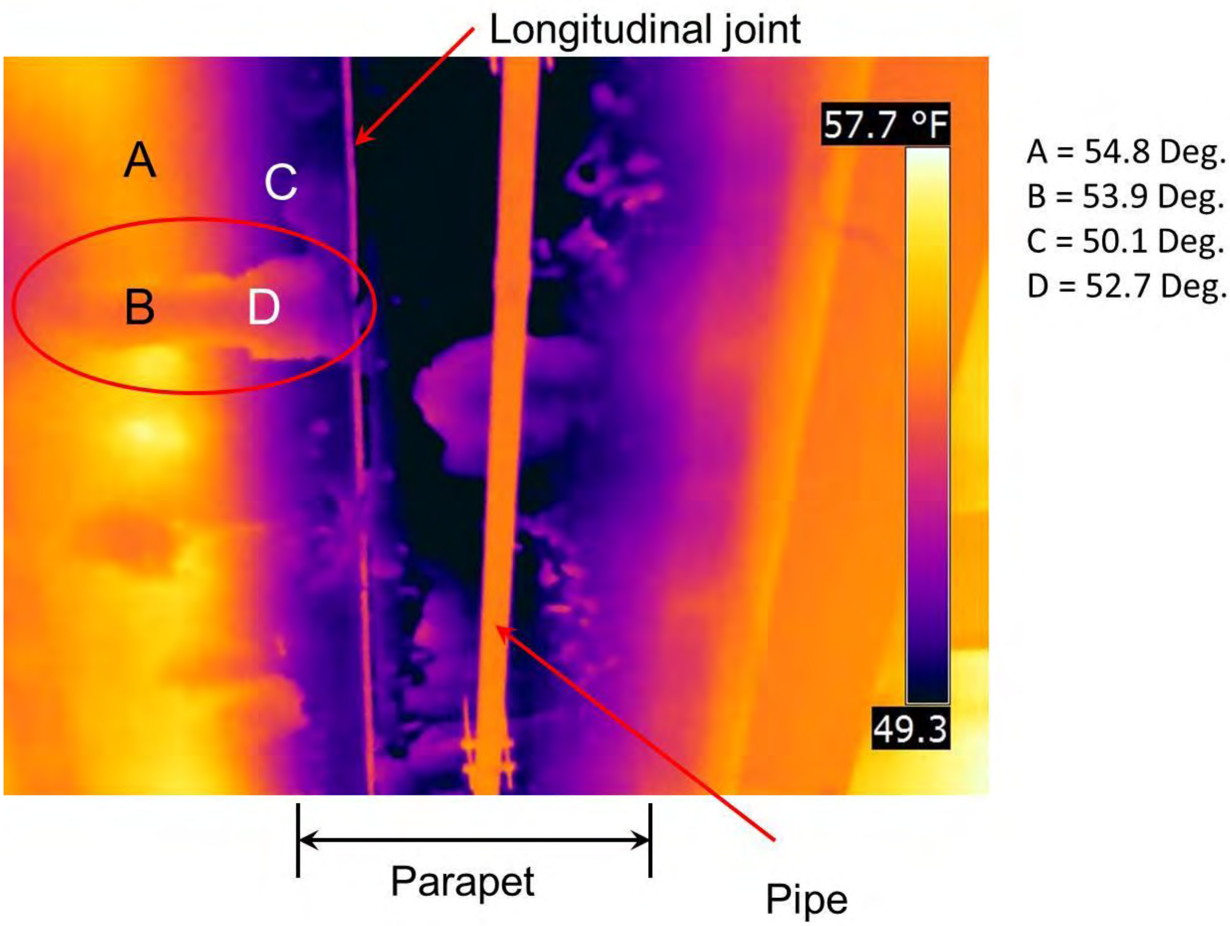


Figure 12: Thermal image of a deck soffit showing the conduction effect on the appearance of concrete delamination at the soffit

3 IOWA

The bridge in Iowa selected for the verification testing was located just northeast of Traer, IA along highway 21. This bridge was chosen because it had delaminations that had been repaired by injecting epoxy into the voids. IR testing was conducted around 8:00 A.M. but only a few small defects at the ends of the bridge were visible. These delaminations were near the surface and had no evidence of epoxy injections.

It was recommended to let the sun heat the bridge and try IR testing at different times throughout the day since the deck had not yet been exposed to the sun for a very long period of time. During the wait time, a chain drag was used to mark out the defects on the deck of the bridge; also, at that time, the soffit of the bridge was inspected. Several spalls and delaminations were visible in the soffit area of the bridge. Figure 13 shows a delamination along the edge of the bridge that was detected with the IR camera which was not clearly visible as shown in image A. The IR image, image B, shows parts of the defect being over 4°F cooler than the surrounding solid concrete.

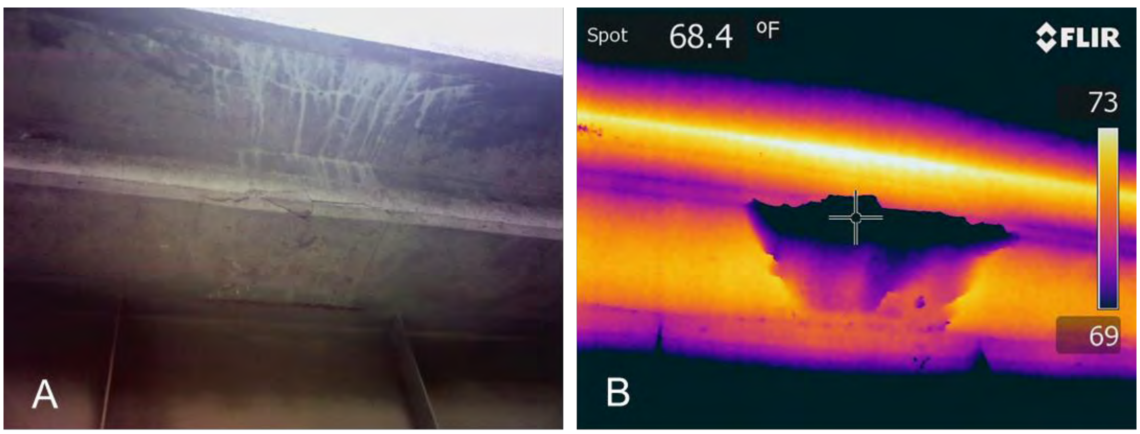


Figure 13: Images of a delamination along the edge of the bridge

IR testing failed to show satisfactory results from the first day of testing so the bridge was revisited a second day. The second day of testing had similar results. The only visible defects in the deck by IR assessment were the defects at the ends of the bridge that appeared to have not been previously repaired and, therefore, had no epoxy. Figure 14 shows the delaminations along the edge of the bridge deck. Image A shows the digital image of the deck while image B shows the IR image. The delaminations appear as white in image B along the edge of the bridge deck.

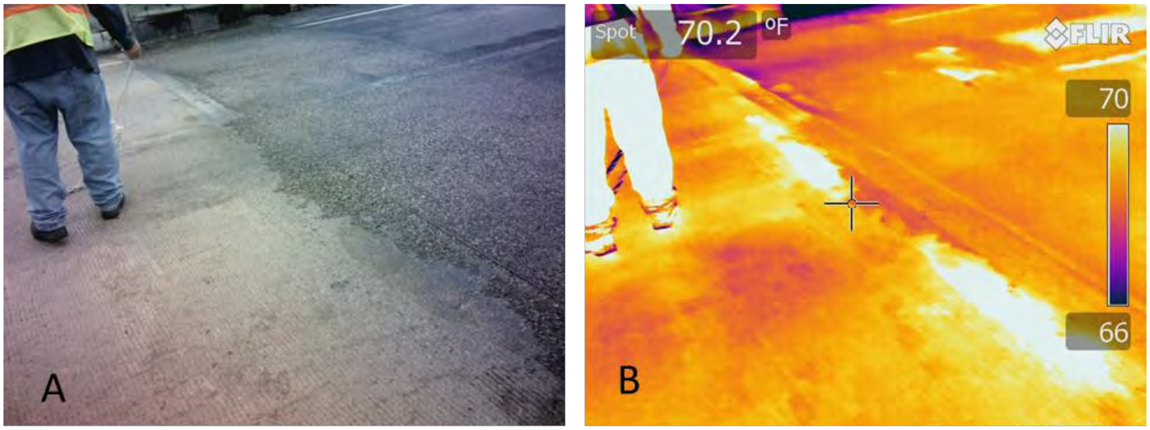


Figure 14: Delaminations along the edge of the deck

Delaminations that had been previously injected with epoxy were also imaged during the testing. Figure 15 shows an area including an epoxy-injected delamination. As shown in this figure, thermal contrast was not observed where the delamination had been repaired by epoxy injection.

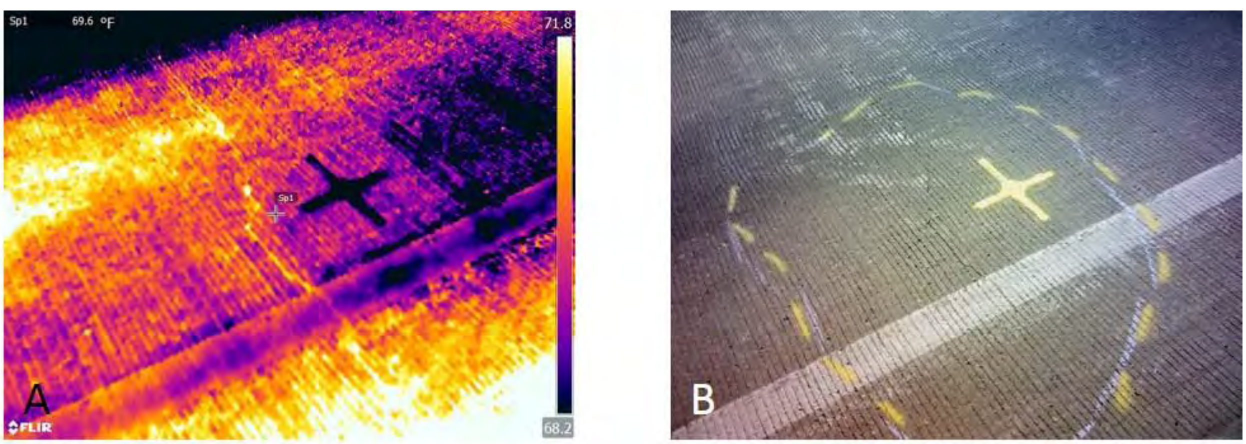


Figure 15: Thermal image showing an area of deck repaired by epoxy injection

Since none of the epoxy filled delaminations were detectable using IR, two of these delaminations were marked for coring. Figure 16 shows the two cores taken from the deck. The cores show one delamination with almost four inches of cover, image A below, while the other delamination had just over two and a half inches of cover, image B below.

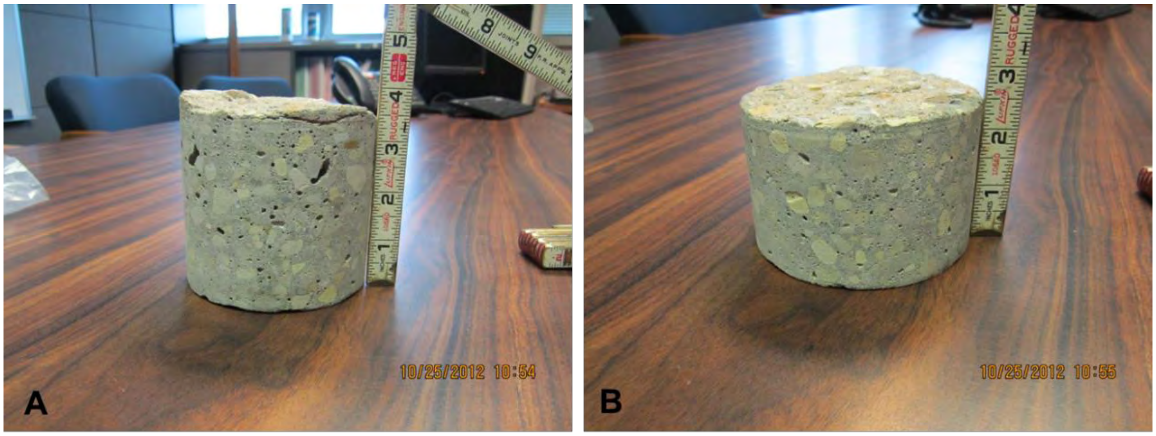


Figure 16: Cores from the delaminations in the deck

The delamination with four inches of cover may have been too deep for IR cameras to detect without almost perfect weather conditions for IR testing. Since the second core had only a two and a half inch cover, it should have been detectable. Since none of the epoxy-filled delaminations were detectable and there was varying cover above the delaminations, a computer model was used to determine if delaminations filled with epoxy, water, or ice are still as detectable as delaminations that have air gaps.

The computer model used data from the test block from phase I of the project to compare voids filled with different materials. The graphs in Figure 17 show defects at two different depths. Graph A shows a delamination at two inches and graph B shows a delamination at three inches; included in each graph are the results if the voids were filled with air (air void), water, ice, and epoxy. The black line shows a delamination with an air gap having a maximum thermal contrast of almost four degrees Celsius in the two inch defect. All of the other filled defects, i.e. water, ice, or epoxy, have a maximum thermal contrast of less than one degree Celsius.

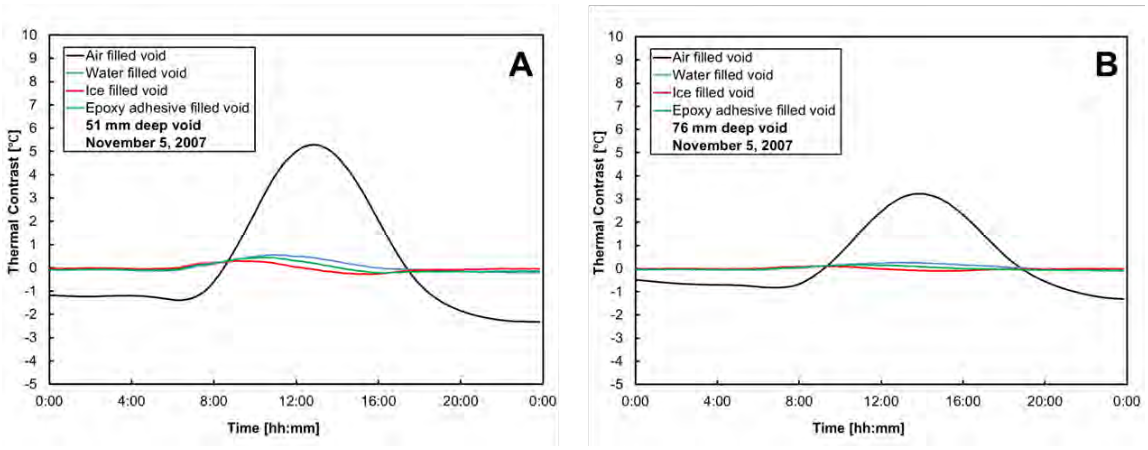


Figure 17: Results from a computer model of filled voids

The computer model along with the test block graphs in Figure 17 confirmed that the epoxy filled delaminations in the bridge were not detectable using IR. While the technology is not able to detect a delamination that has been repaired with epoxy, it can be used as a quality control technique. Any delaminations that are filled with water, ice, or epoxy will not be detectable; this means that repaired delaminations will not show up (Nelson). Figure 18 displays the ambient temperature in the hours leading up to and the hours after testing.

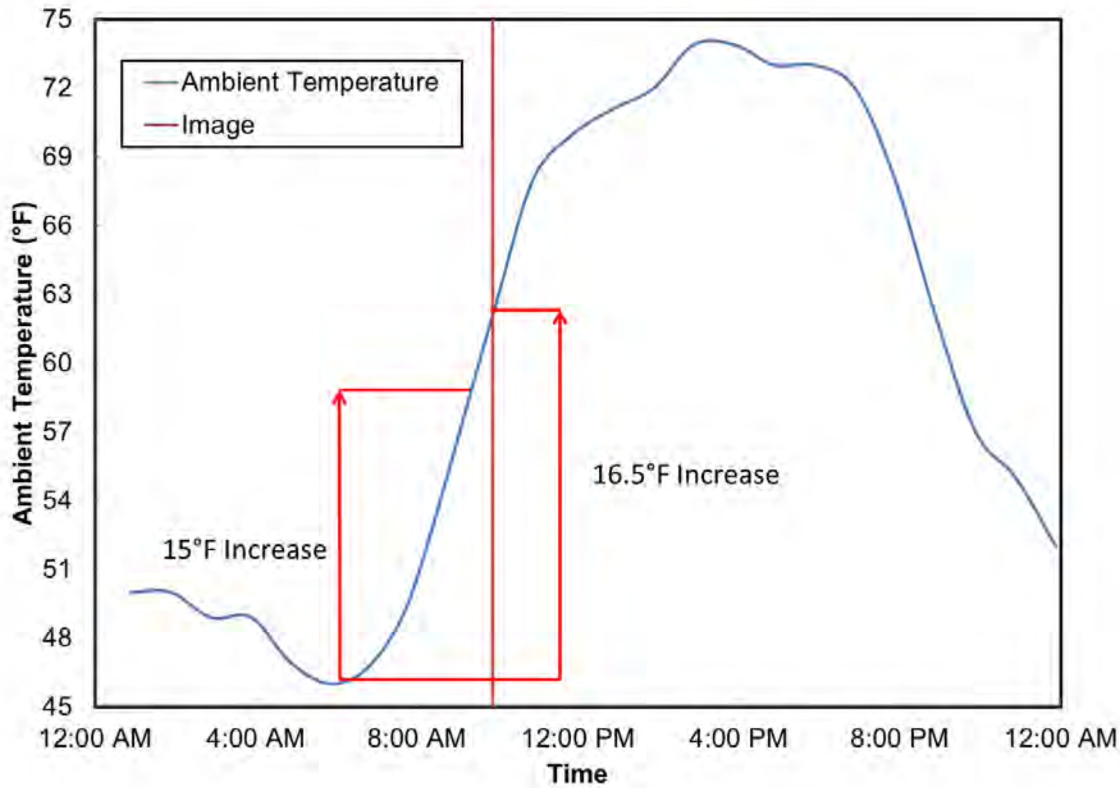


Figure 18: 24 hours of ambient temperature surrounding the testing

3.1 IR-UTD Test Verification

A second bridge in Iowa was field tested for the purpose of IR-UTD testing. This bridge's deck would be going through the repair process of injecting epoxy into the delaminations. In addition to the IR-UTD system, verification was also accomplished with the handheld infrared camera and borescope.

The Iowa Department of Transportation sounded the entire deck to locate the areas where epoxy injections were going to be necessary. Infrared images were taken at most of these locations; in addition, borescope measurements were taken at one of the larger delaminations. The borescope allows researchers to inspect the inside of the structure by taking a small camera and inserting into a hole drilled into the deck; in this way, a picture of the delamination is captured. An image of a large deck delamination can be seen in Figure 19 below.

Images were also taken of the same delamination on the soffit of the deck. The soffit image can be seen in Figure 20 below.

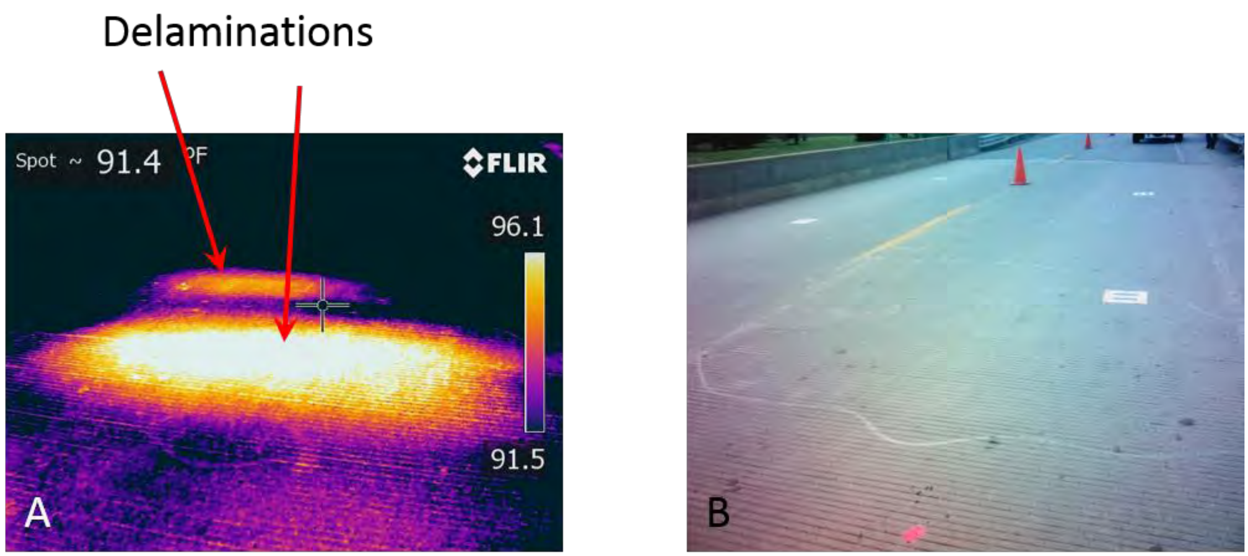


Figure 19: Infrared (A) and Digital (B) images of a deck delamination in Lamoni, IA

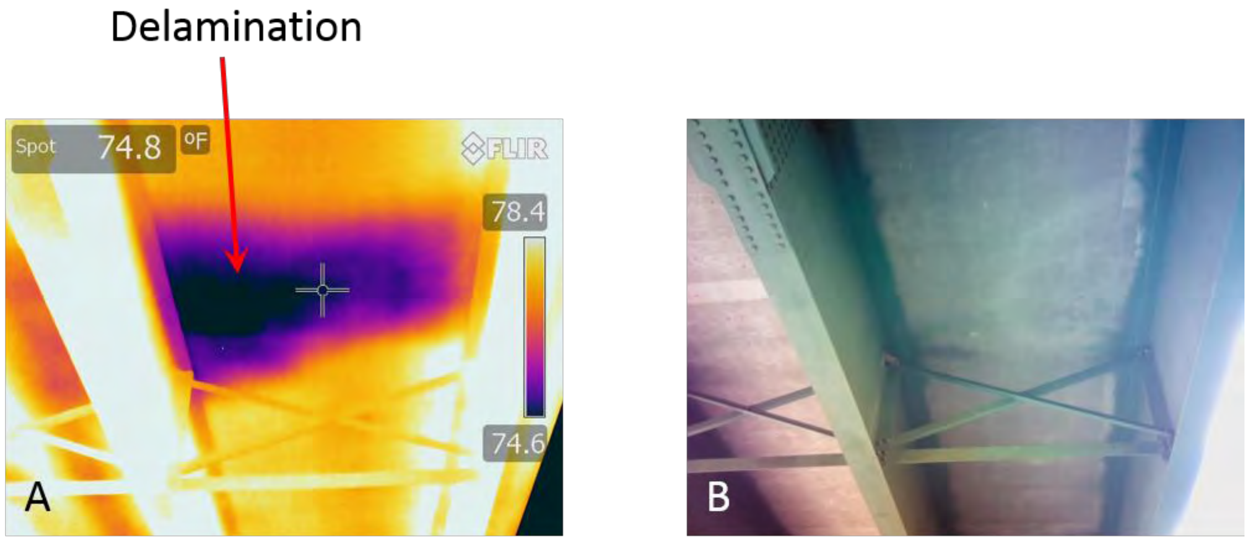


Figure 20: Infrared (A) and Digital (B) images from the soffit of the delamination in Figure 19

The images from Figure 20 were captured at 3:22 P.M. An observation that has been made over the course of the project through verification is that delaminations on the deck show up as "cold spots" on the soffit in the afternoon. The inability of the heat to transfer through the depth of the deck because of the air void is the cause of the "cold spots".

The borescope was also used to verify the depth of the delamination. Sixteen locations throughout the area of the delamination were measured. The depths and locations of each measurement can be seen in Figure 21 below.

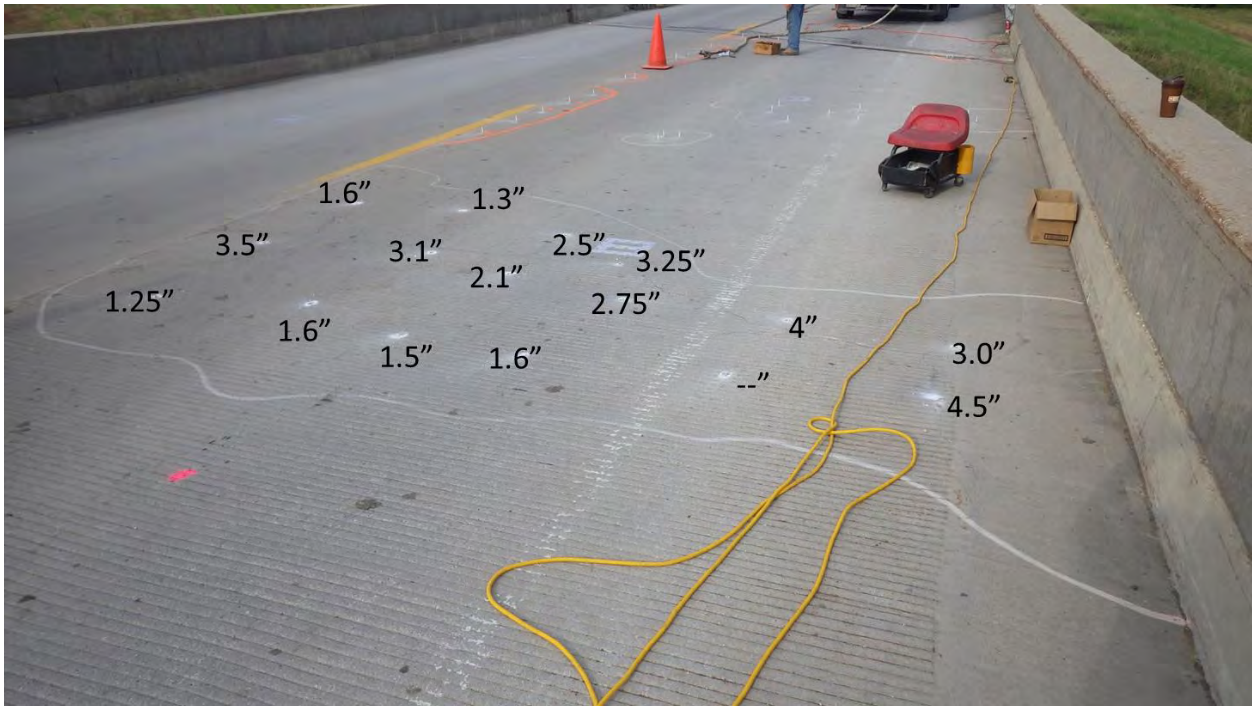


Figure 21: Drilled hole locations for borescope measurements

In order to measure the depth of the delaminations, the borescope was inserted into the hole to the point where the crack could be seen. Measurements were gathered from the length of the stick and how far the borescope had been inserted. Figure 22 shows an image captured with the borescope. Figure 23 shows a schematic diagram of how the borescope is used.

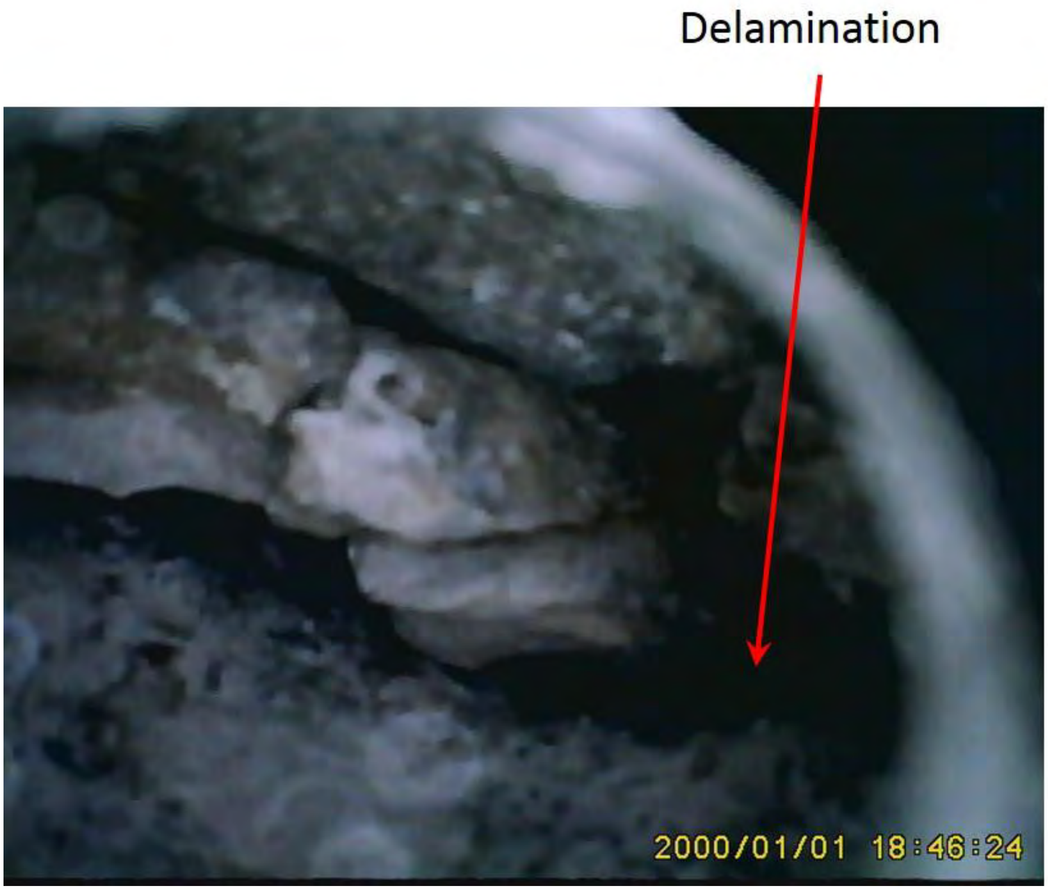


Figure 22: Borescope Image from location 6

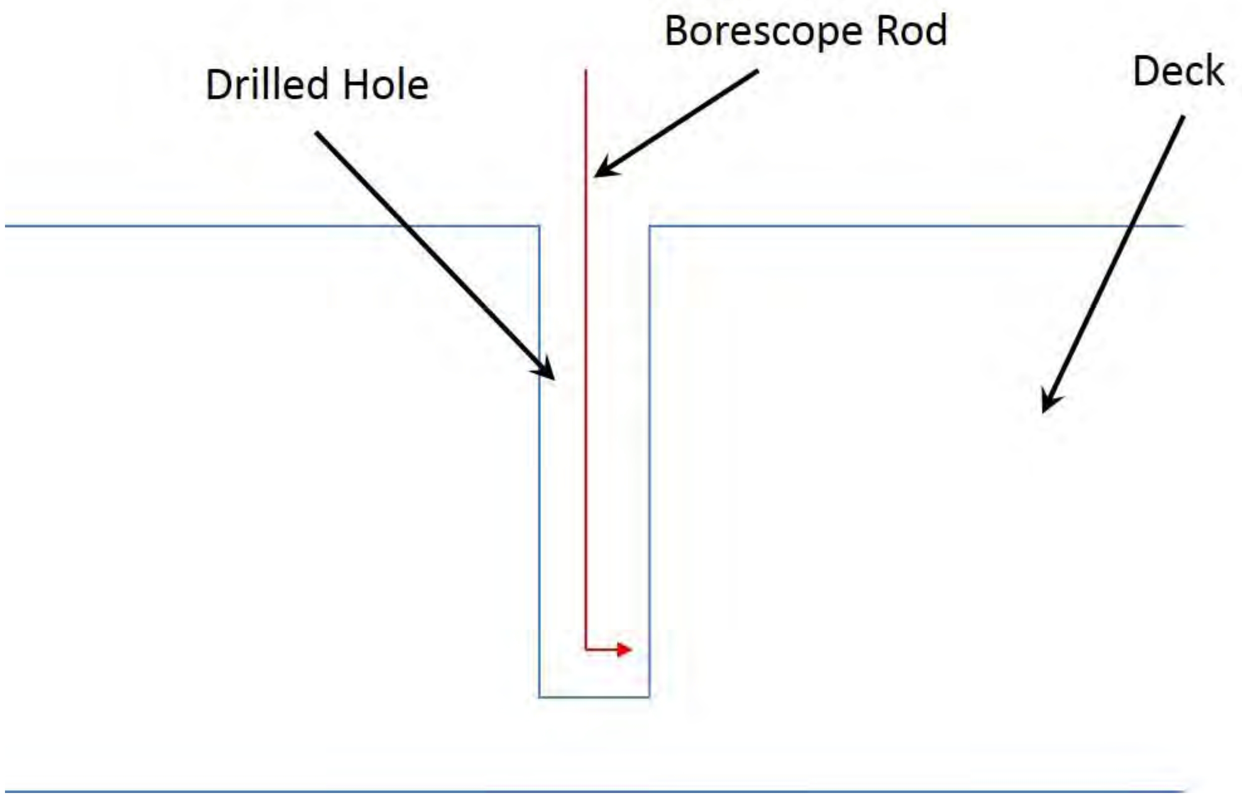


Figure 23: Schematic diagram of how the borescope is used

Weather conditions for the day were good for infrared thermography. The wind speed was as high as 16 mph but was between 6 and 9 mph for most of the day. The guideline suggests a threshold of 15 mph. With more ambient temperature change, the amount of wind must increase significantly to become detrimental to inspection. The ambient air temperature is shown in Figure 24 below.

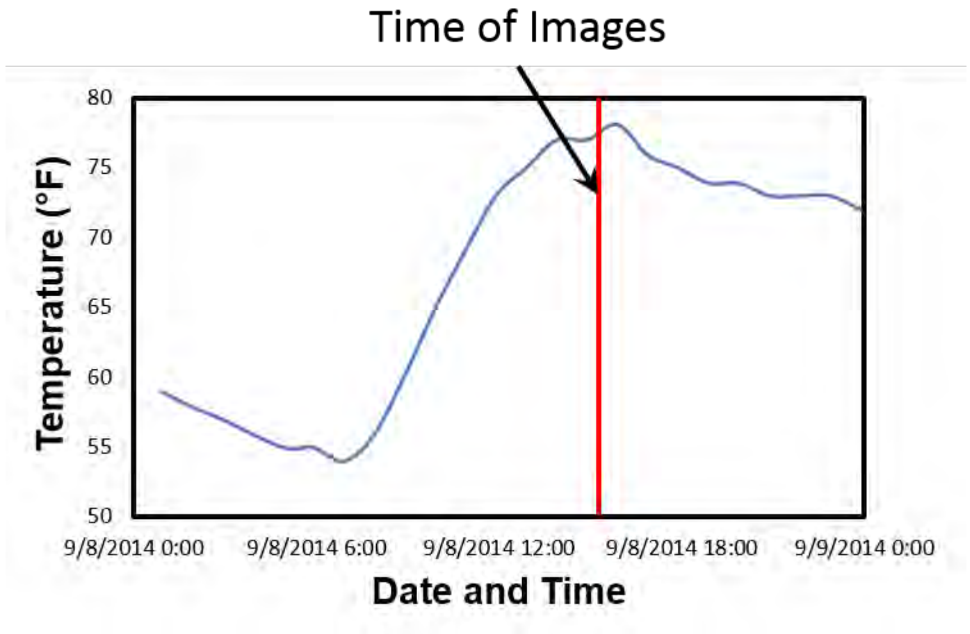


Figure 24: Ambient temperature for verification in Lamoni, IA

4 GEORGIA

The November 2012 trip to Atlanta yielded no results due to poor weather conditions; this trip was unsuccessful pertaining to verification. This was one of three state trips that were unsuccessful. There was rain and very little temperature change throughout both days of the trip; rain is completely detrimental to bridge deck inspection and no quality images could be taken for that reason. The time during this trip was spent working with the inspectors to review guidelines and the process of uploading images to the thermography website. A graph of the ambient temperature during this time frame is shown in Figure 25 below.

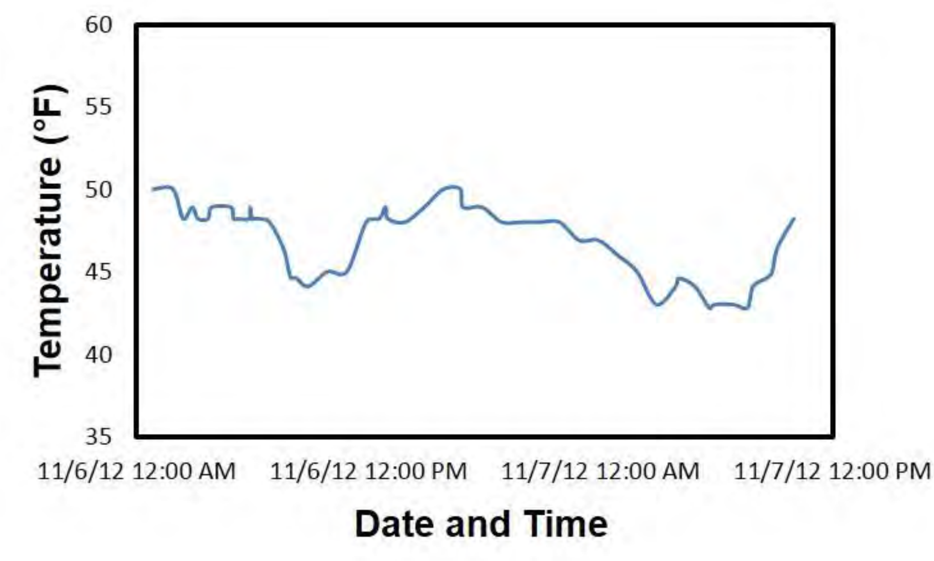


Figure 25: Ambient air temperature for the verification trip to Georgia (2012)

A total of three locations were tested on the return trip: Johnstonville Rd. spanning I-75; Dames Ferry Bridge deck spanning the railroad track; and Dames Ferry Rd. Bridge spanning the Ocmulgee River. The trip was carried out May 28th, 2014 near Forsyth.

The weather conditions for this trip were ideal for thermographic inspection since there was sufficient ambient temperature change and little to no wind. Figure 26 shows the ambient temperature.

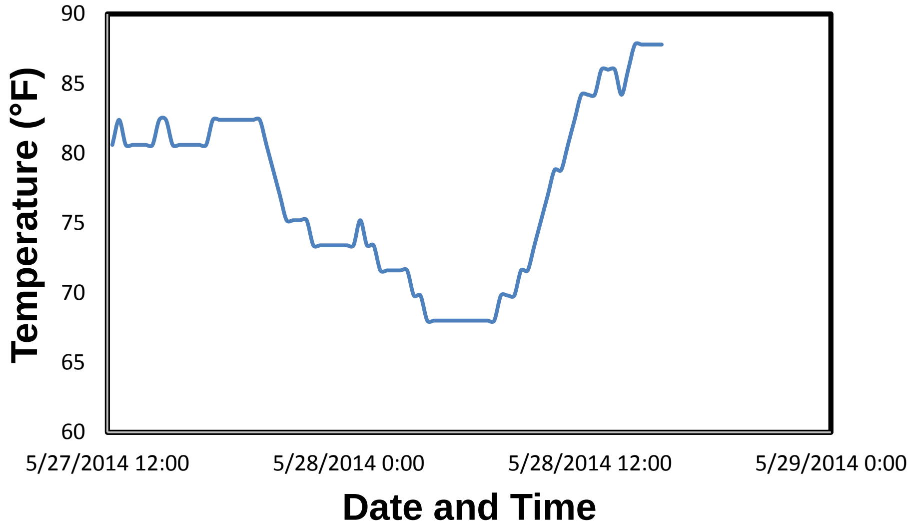


Figure 26: Ambient air temperature for the verification trip to Georgia (2014)

In order to verify the I-75 Bridge, GDOT workers hammer sounded the deck and marked delaminations with bright orange spray paint. The Georgia Bridges had been hammer sounded prior to this May 2014 trip, but the markings had washed away. After the initial assessment with hammer sounding, inspectors employed the infrared camera to detect delaminations. Since the IR inspection was performed in the ten o' clock hour, the deck had not experienced enough of a temperature change to yield desirable results. To allow for a larger temperature change to occur, a return trip was made to the bridge at approximately 3 P.M. Figure 27 shows an example of the results for the Johnstonville Road Bridge spanning I-75.

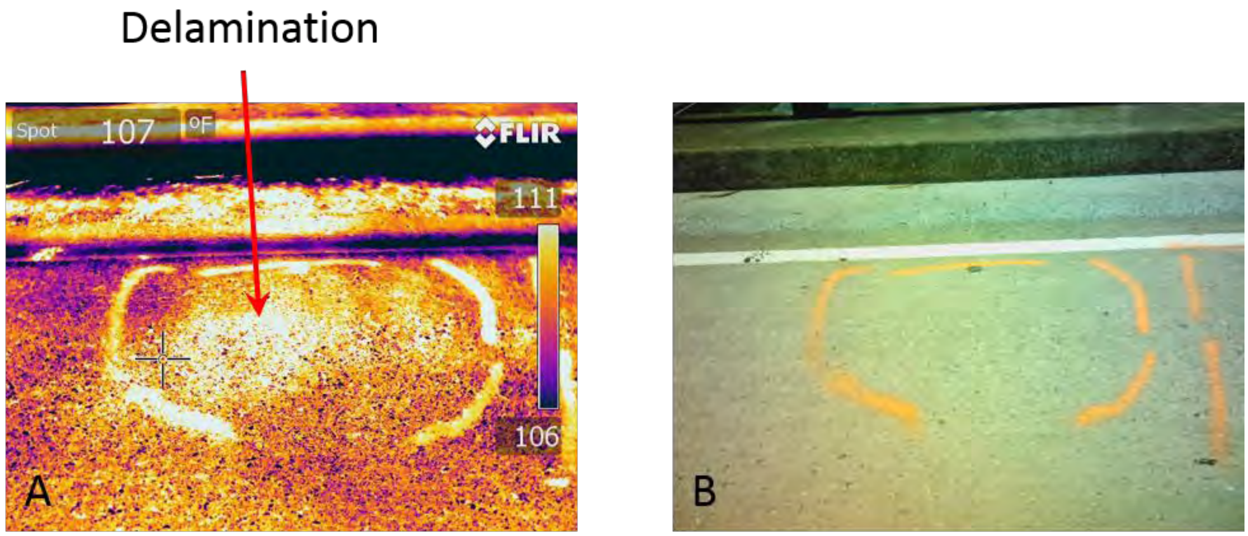


Figure 27: IR (A) and digital (B) images of a deck delamination on Johnstonville Rd.

The infrared camera was used as the initial inspection tool on both of the Dames Ferry Road bridge decks; verification was completed with hammer sounding. The bridge over the railroad tracks provided excellent results. Examples are shown in Figures 28 and 29.

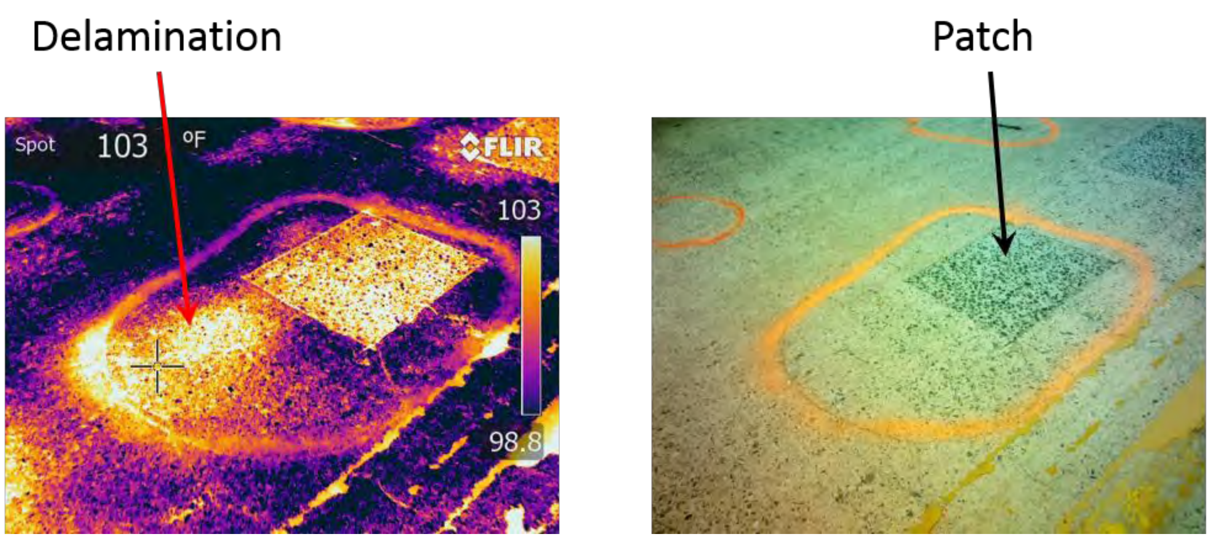


Figure 28: IR (A) and digital (B) images of a deck delamination over Ocmulgee River

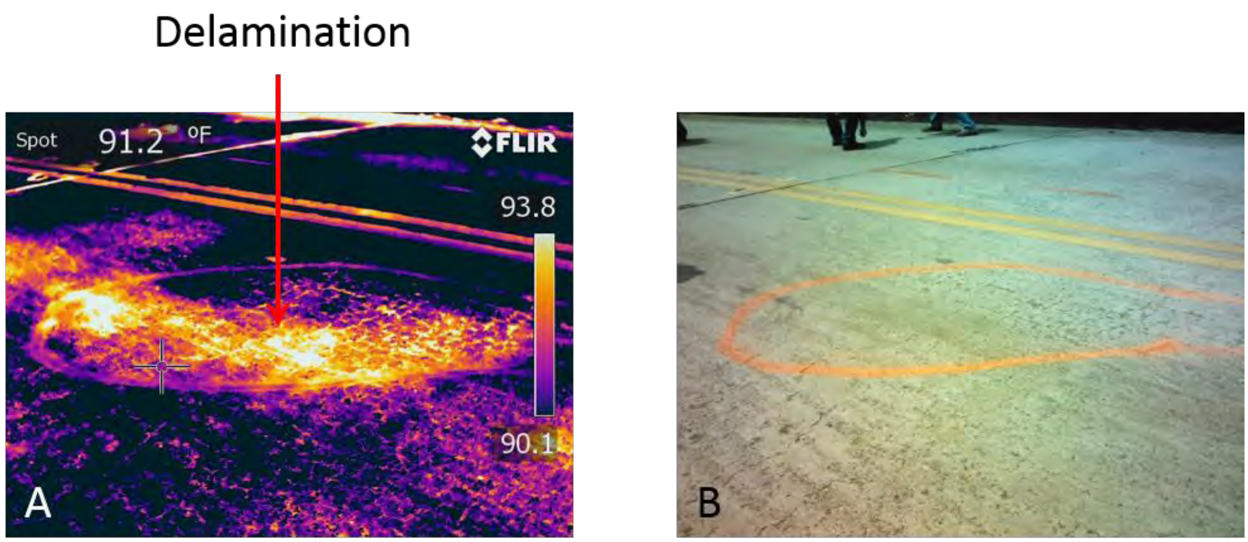


Figure 29: IR (A) and digital (B) images of a deck delamination over a railroad on Dames Ferry Rd.

Figure 28 illustrates a delamination near the edge of a patch in the deck. Delaminations sometimes form near the edge of patches as a result of the original repair (i.e. patch) not being fully effective as a repair of the damage in the deck. This example illustrates the application of thermography for identifying additional repair needs.

5 PENNSYLVANIA

A bridge on I-376 over the Shenango River was tested on April 29th and 30th, 2013. The weather for the April 29th IR inspection of the bridge was not conducive to producing thermography images. The temperature at the time of inspection did remain fairly constant although an 11 degree temperature change occurred later in the day. The wind was calm as it never exceeded 7 mph during inspection (Wunderground).

Figure 30 provides a graph of the ambient temperature change for both days of the Pennsylvania bridge inspection.

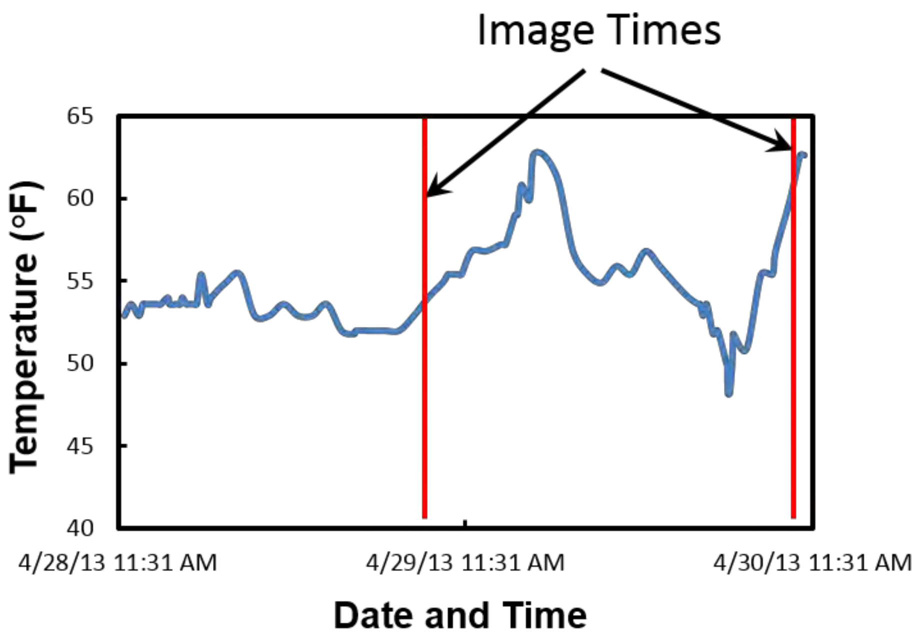


Figure 30: Ambient air temperature for the verification trip to Pennsylvania

Scattered showers throughout the day interfered with the deck inspection; therefore, the substructure was inspected instead. Although weather conditions were less than ideal, a delamination could still be seen in one of the pier caps. A thermal and digital image of the delamination can be seen in Figure 31 below.

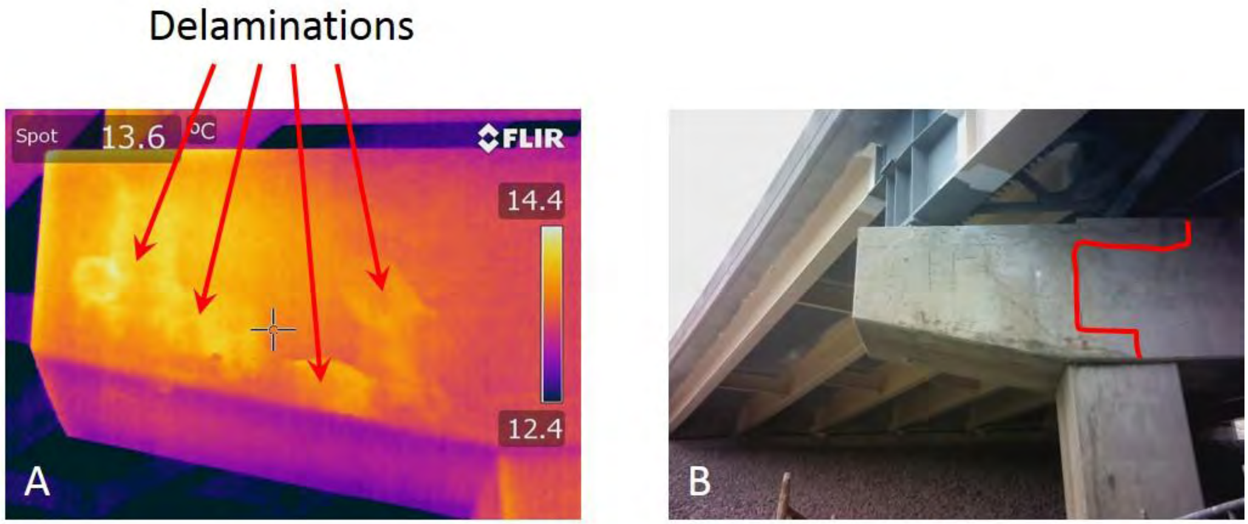


Figure 31: Thermal image (A) and digital image (B) of a pier cap delamination

It is challenging to see but the pier cap was sounded and marked with a black marker. The edge of the marking is above the left side of the column in the image above. It has been traced for clarity.

On the second day of testing, an early morning rain caused water to collect on the deck. However, by about 10:00 A.M. the deck started drying out and pictures were taken from the boom of a truck. The truck is shown in Figure 32. The change in temperature during the three hours of inspection time was 7°F. The wind speed varied over the inspection period but never exceeded 9 mph (Wunderground). An image from the boom can be seen in Figure 33. Additional images from this test are available on the SDS.

Figure 32: Boom truck used for elevated images in Pennsylvania

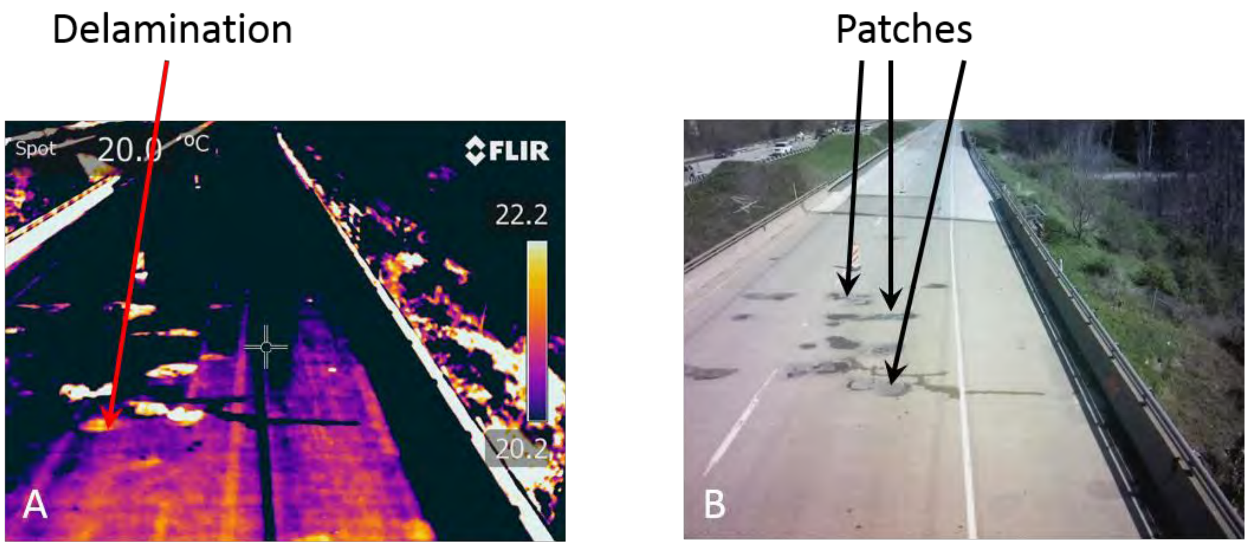


Figure 33: IR (A) and digital (B) images from a boom of a deck in Pennsylvania

Figure 33 illustrates the ability of infrared thermography to distinguish between delaminations and patches on the deck. Patches in the deck are easily identified in the digital image and can be paired with the infrared image. Delaminations are not visible in the digital image.

6 TEXAS

Multiple bridges in Texarkana were inspected and verified on May 29th and 30th, 2013. One bridge was of particular concern since there was some transverse cracking in the deck. The concern was in regards to separation in the precast panels and cast in place concrete. A delamination due to the separation of the deck from the precast panels would be at a depth of approximately four inches. It was expected that detection would be difficult even under extremely good weather conditions;

Due to less than ideal weather conditions for thermographic inspection, the trip was unsuccessful. On May 29th, the change in temperature was 15°F with a wind speed of 14-18 mph during the time of inspection and cloudy conditions (Wunderground). Clear, sunny skies would be preferred when deck inspection is the concern. The temperature and wind parameters were also at the edge of the guidelines. Figure 34 shows a graph of the ambient temperature for the trip to Texas.

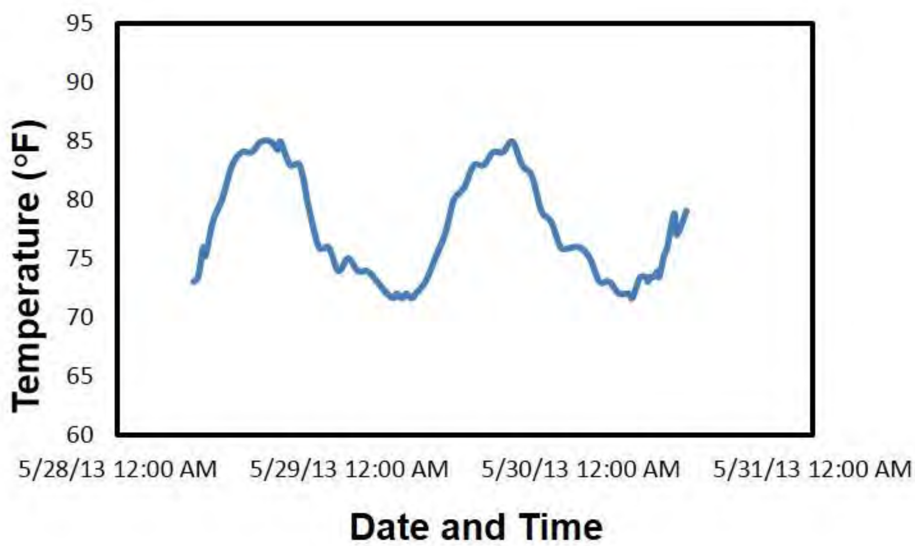


Figure 34: Ambient temperature for the verification trip to Texas

The weather conditions on May 30th were similar to May 29th with the exception of the temperature change during the time of inspection. With the combination of the depth of possible delaminations and less than ideal weather conditions, no quality thermal images could be taken.

7 OREGON

The Oregon bridge chosen for verification testing was completed on a bridge at Crosby Rd. over I-5, north of Woodburn. Testing was accomplished on August 8th, 2013. The Oregon Department of Transportation had performed a previous inspection with the report completed by Wiss, Janney, Eistner Associates Inc.; this inspection included findings of delaminations in the soffit and Reinforced Concrete Bridge Girder (RCBG) in the middle bent of the bridge.

7.1 Results and Analysis

The weather for the day was ideal for infrared thermography. Infrared imaging for the use of bridge inspections requires certain weather conditions for quality images. The weather for the day of inspection included a low temperature of 57°F with a high of 84°F. The wind speed for the day was 5 mph with no precipitation. Sunrise occurred at 6:04 A.M. with a temperature of 57°F. The temperature at 12:04 P.M. was just above 71°F (Wunderground). A graph of the ambient temperature can be seen in Figure 35.

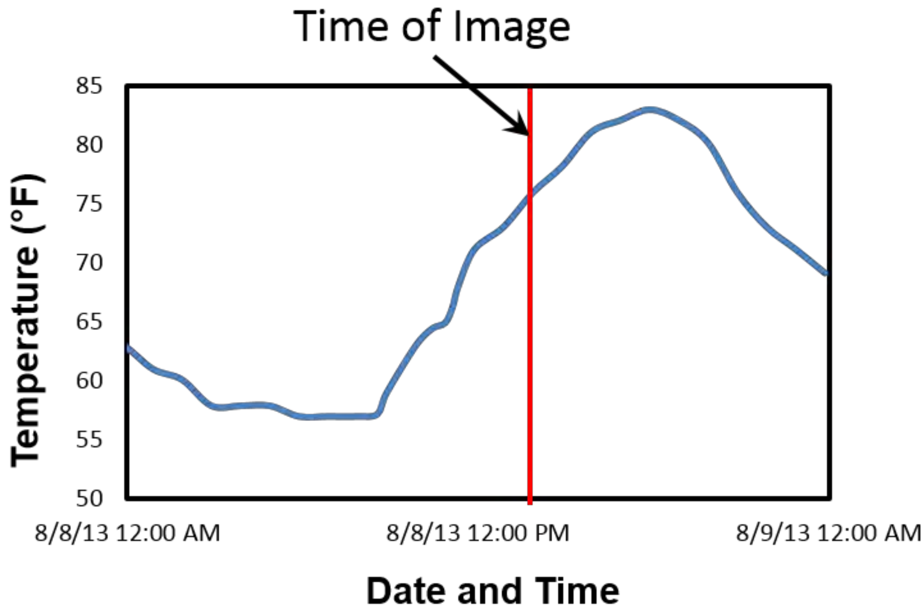


Figure 35: Ambient temperature for the verification trip to Oregon

Figure 35 shows 14 degrees of temperature change in the first six hours when only 10 are needed for a good inspection day.

Images of the sounding results from the report, along with the corresponding delamination near one of the drains, are shown in Figures 36 and 37 below. The sounding results are outlined in black for clarity.

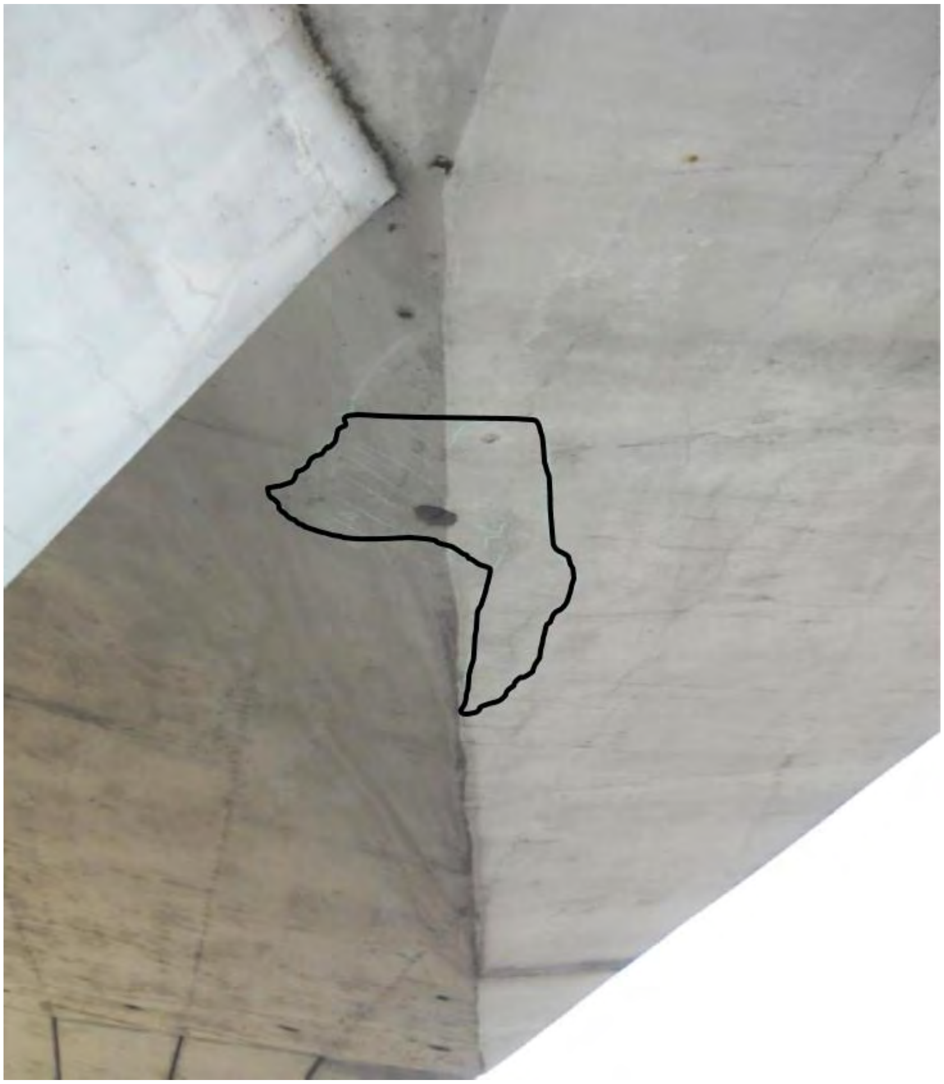


Figure 36: Hammer sounding results of a drain delamination from the WJE report

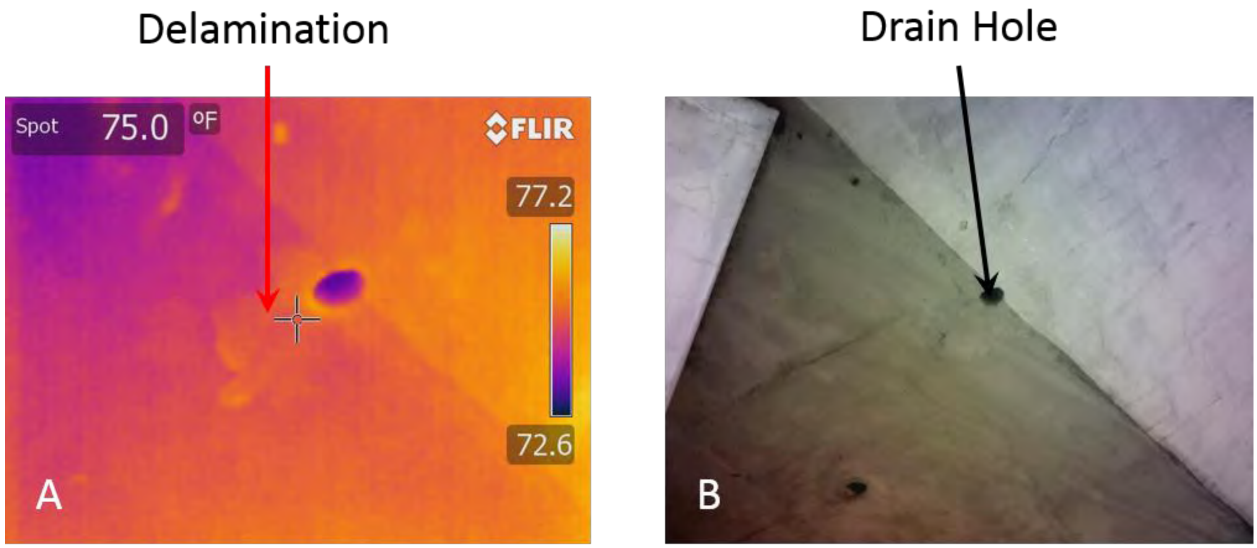


Figure 37: Thermal image (A) and digital image (B) of a drain delamination

Figure 37 was captured at approximately 2:30 in the afternoon when the temperature was about 77 °F. The temperature in the day had changed 20 degrees and should have been sufficient to capture a quality image. As it can be seen above, the image seems to barely show a temperature difference with the smallest span possible for the camera.

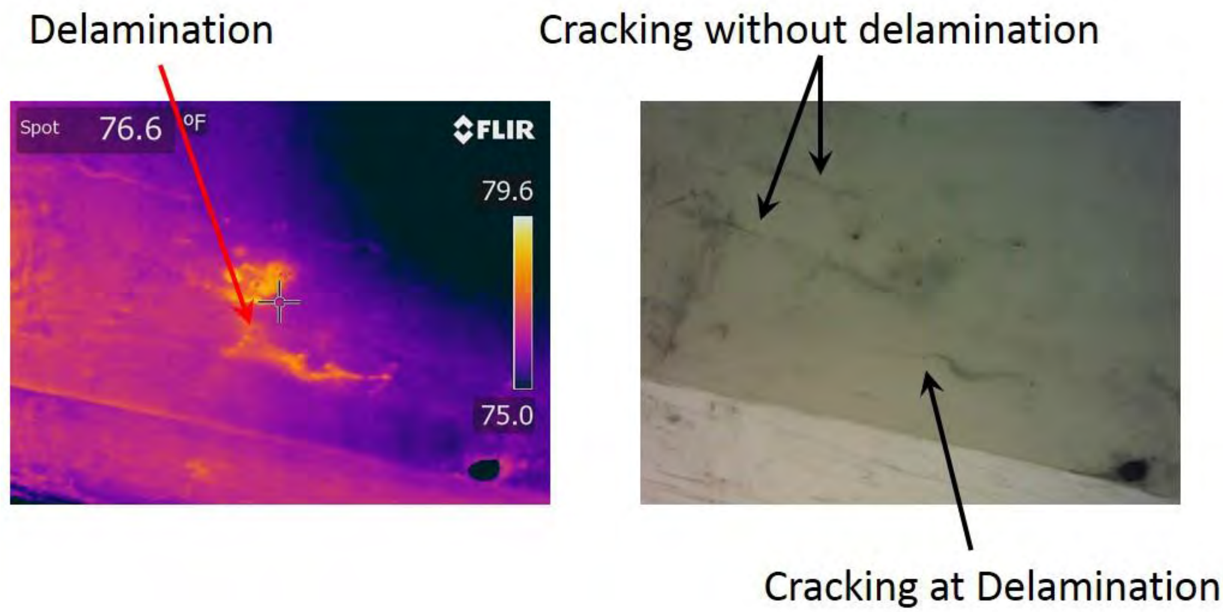


Figure 38: IR (A) and digital (B) image of a possible parge coat delamination

Figure 38 illustrates a possible delamination in the parge coating. There are other cracks similar to the area in question that show no evidence of thermal contrast. The fact that there is no thermal contrast in other areas leads us to believe that this is a delamination, not in the concrete, but in the parge coating.

7.2 Conclusions

The goal of the inspection for this bridge was to capture quality thermal images of delaminations that had been previously detected by the Oregon Department of Transportation. The weather conditions for the day were more than sufficient enough for quality images to be captured. However, the images captured did not show the typical results with good conditions.

A possible cause for the lack of quality images could be due to the fact there was a parge coating applied to the bridge (Wiss). The irregularities compared to the concrete underneath the coating may have caused poor results.

The verification trip can still be considered a success because of the lack of prior knowledge or experience with parge coatings and their effect on thermal imaging. Normally, images are captured on the deck where parge coats are not applied. It is now known that, even in ideal weather conditions, parge coatings can affect the way a delamination will appear in a thermal image.

8 KENTUCKY

The Kentucky verification trip was completed August 26^{th}, 2013 and completed in Louisville. The bridge that was chosen was part of the Ohio River Bridges Project in connection with the Kentucky Department of Transportation. As part of this project, bridges are being replaced and this makes them good candidates for verification testing. Before the decks are removed for replacement, IR inspections can be completed, as well as sounding and removing cores.

A bridge on I-265 over Kentucky St. with delaminations in a large abutment wall, piers, and pier caps was tested. These three components had been sounded and the areas designated for repair had been marked. Example images are shown in Figures 39 and 40 below.

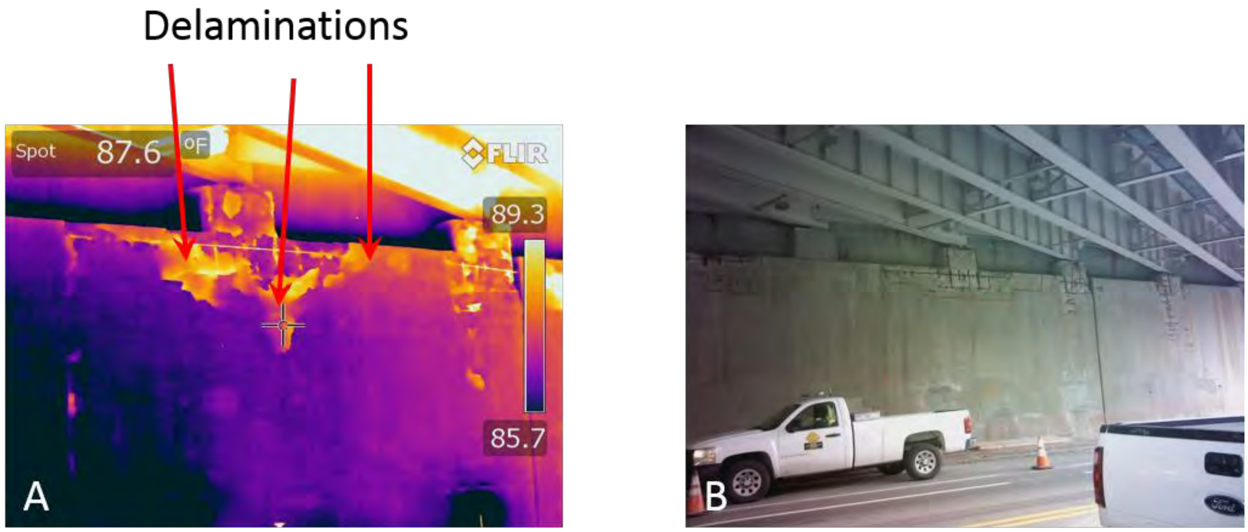


Figure 39: Thermal (A) and Digital (B) images of a delaminated abutment wall under I-265

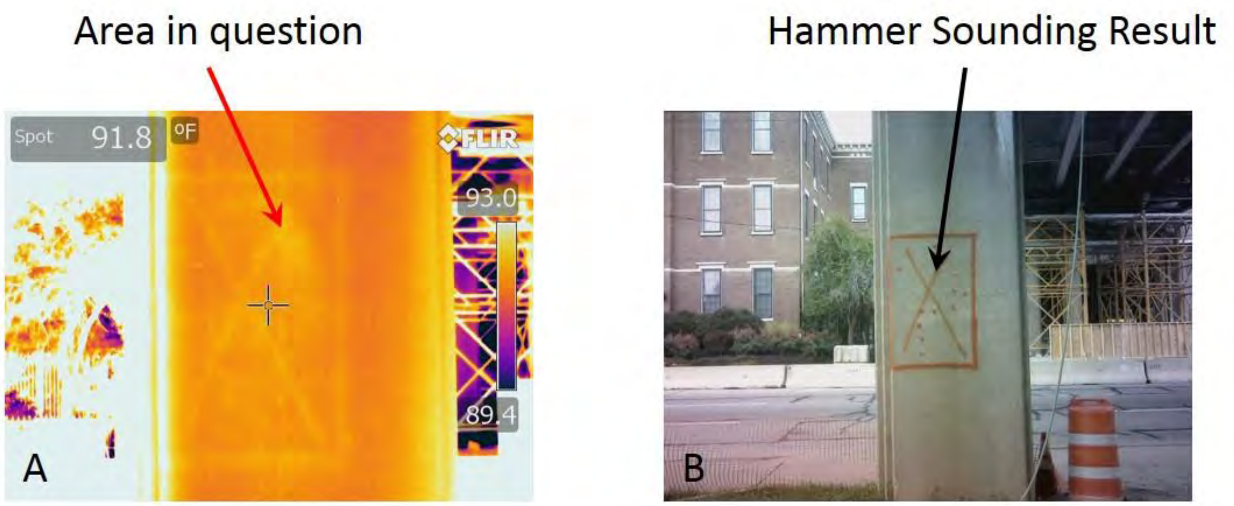


Figure 40: IR (A) and digital (B) images of hammer sounding results on a pier in Kentucky

The comparison of the thermal and digital images, along with more images on the pooled fund website, show that some of the areas the inspectors did not mark are delaminated. Since replacing concrete is typically done on a per square foot basis, minimizing the amount that has to be replaced and ensuring that all the delaminated concrete is removed is a primary objective of repair. The infrared results and the hammer sounding may not always match. Hammer sounding is an objective approach to inspection and may vary by inspector. The infrared camera has the ability to optimize the process and saves much of the sounding time in the process. Instead of sounding the entire abutment wall, the camera can identify where the problem areas are and sounding can be used to verify delaminations.

There was also a case where the inspectors hammer sounded a delamination that the infrared camera did not identify. Further analysis of the image was completed using a computer program called FLIR tools. The analysis showed that a 0.5° F contrast existed between the area in question and the surrounding concrete, however, this relatively small thermal contrast was not identifiable in the field.

It was a very good day for infrared thermography. The weather for the day included a temperature change of 19°F with approximately 13°F of that occurring in the first six hours after sunrise. The wind speed for the day got as high as 12 mph but was 5 mph at the time of the inspection (Wunderground). A graph of the ambient temperature is shown in Figure 41.

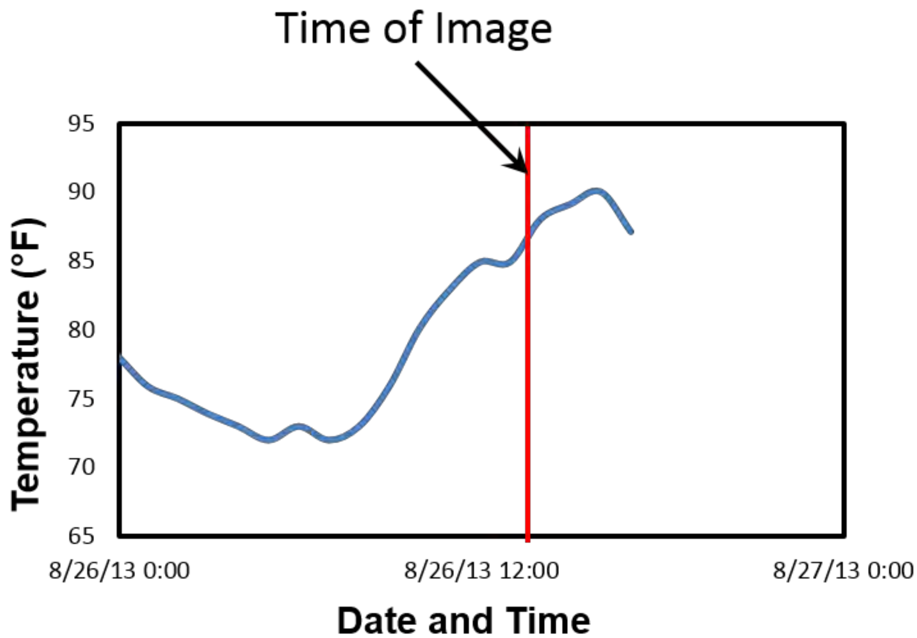


Figure 41: Ambient temperature for the verification trip to Kentucky

9 NEW YORK

The verification testing was conducted on a pair of bridges at Albany Shaker Rd. under I-87 and was completed November 20th, 2013 just north of Albany. The bridges were built in 1959. A previous inspection from November 2012 was completed and provided by the New York Department of Transportation. The inspection included findings of delaminations in the pier columns and caps.

The ambient temperature change can be seen in Figure 42. This image is taken from the weather checker on the pooled fund website. It displays both the previously recorded data along with the forecasted data.

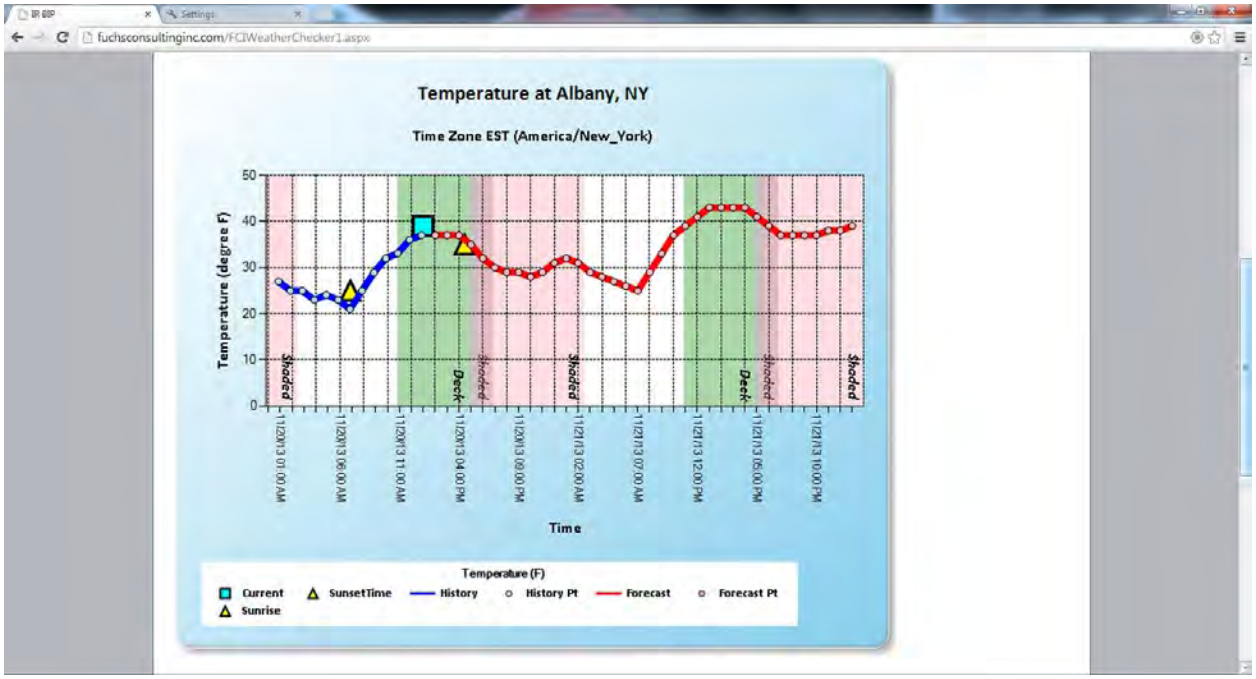


Figure 42: Previous and forecasted weather conditions provided by the weather checker

Three sets of images were taken on the New York verification trip. The times of the images were at roughly 8:00 A.M, 11:00 A.M. and 2:00 P.M. The lack of sunlight later in the day, along with a high traffic volume in the area, would have made it extremely difficult for a night inspection. An image of a pier column can be seen below in Figure 43 and more images can be seen on the pooled fund website.

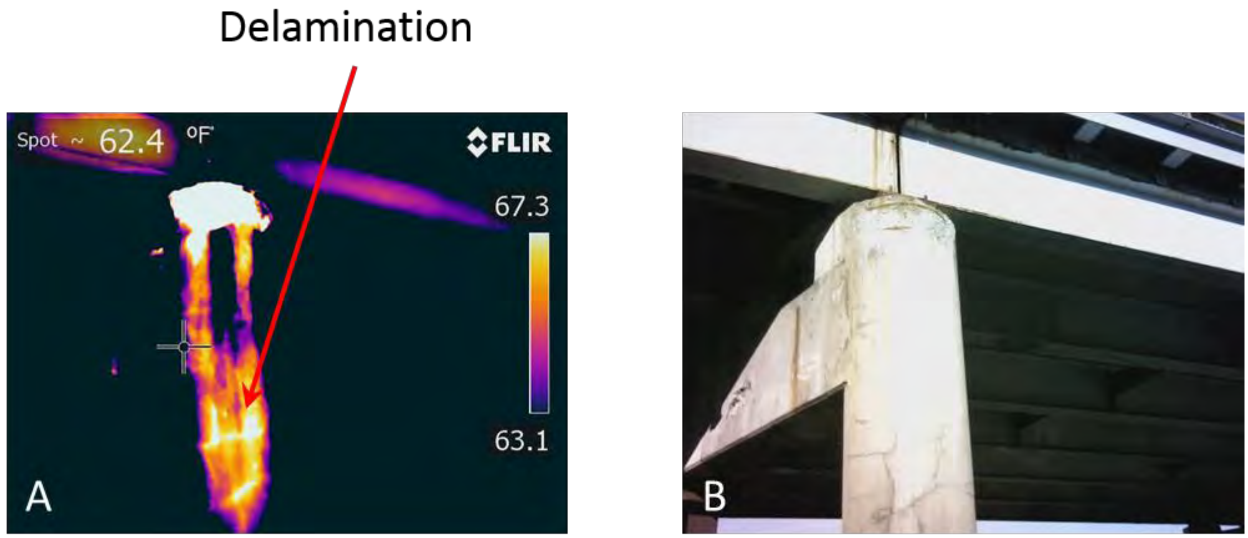


Figure 43: IR (A) and digital (B) images of a delaminated column on Pier 1 of South Bridge

An extreme thermal gradient is evident in the figure. The digital image shows that the sunlight is directly hitting the delaminated area which provided better thermal imaging results. The delaminated area can be seen as the “hot spots” in the picture. This is referred to as Pier 1 in the report provided by NYSDOT. The report lists this particular column as having map cracks with rust stains. It is possible that the cracks may have propagated in the past year to form what are now delaminations.

To further demonstrate how a thermal gradient can affect an image, Figure 44 shows four of the same image with four separate spans: 10 (A), 20 (B), 30 (C) and 40 (D). A typical span for capturing a good image in the field is approximately 4-8°F. For this example, a span of 40° F is required for everything in the image to appear.

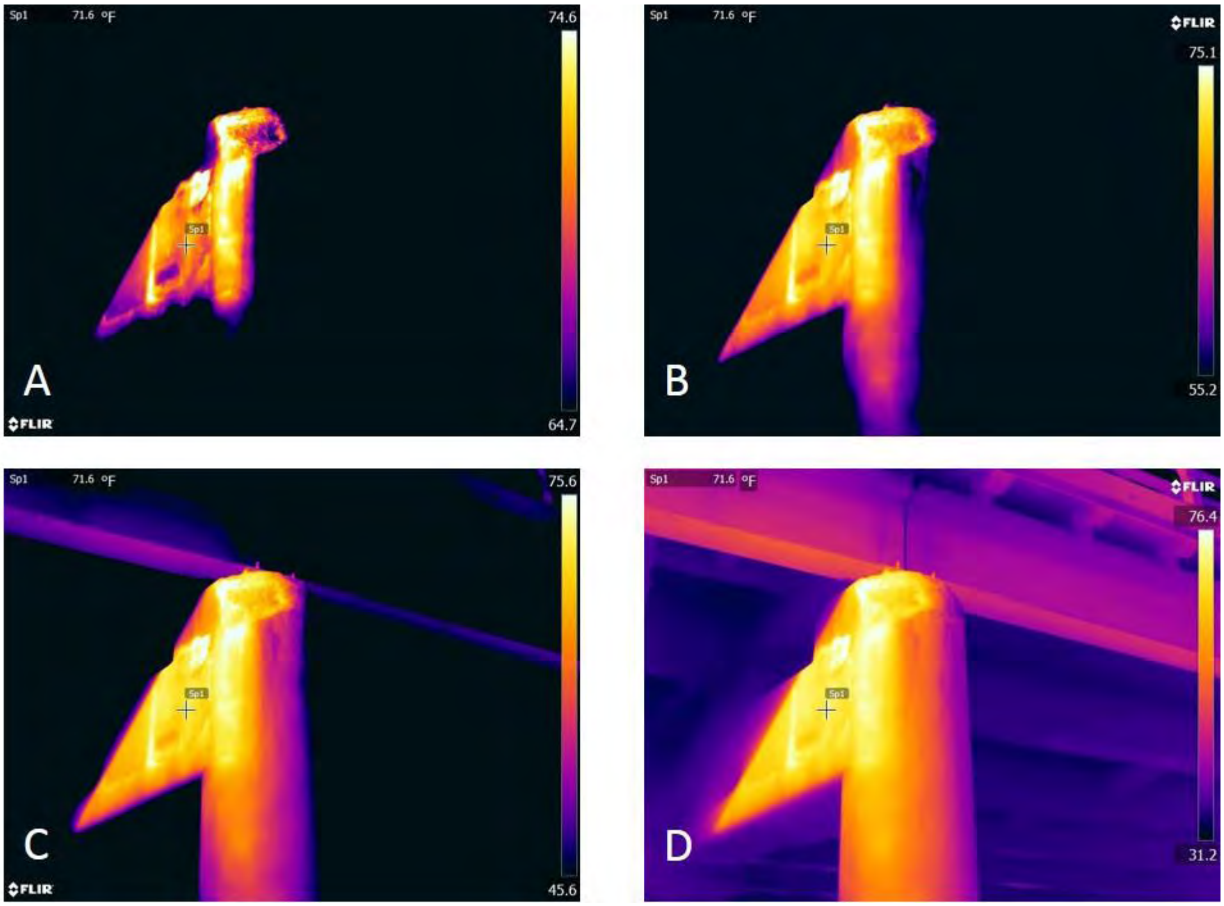


Figure 44: Illustration of how thermal gradient can affect an image

The goal of the inspection for this bridge was to capture quality thermal images of delaminations that had been previously detected by the New York State Department of Transportation. The weather conditions for the day were sufficient enough for quality images to be captured. The thermal gradient of the transition from sun affected areas to non-sun affected made it difficult to capture quality images in some areas. However, there was a greater temperature contrast in the areas that the sun was affecting. An effective solution to the thermal gradient issue would be to capture images at night when there is no exposure to sunlight.

10 FLORIDA

No verification trips have been made to Florida at this point in time but there had been some verification testing accomplished during training. The training was completed April 29-30th, 2014 in Tampa, Florida. The first day was spent in the classroom going over the fundamentals of infrared thermography and reviewing how to use the camera. The second day was spent travelling to the testing location on the North Sunshine Skyway fishing pier. That pier was part of the original structure that spanned the bay before the Sunshine Skyway Bridge was constructed. The testing was done on the deck of the fishing pier. An example of a delamination can be seen in Figure 45.

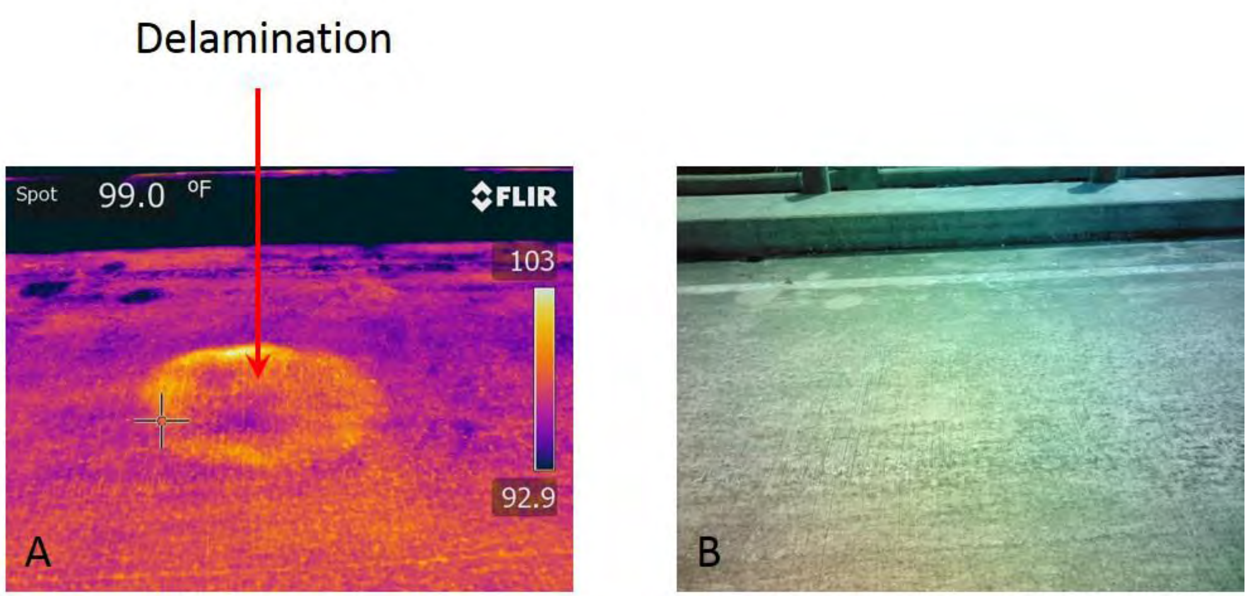


Figure 45: Infrared (A) and digital (B) images of a deck delamination in Florida

Given the temperature change and wind conditions, it was a good day for infrared thermography based on the inspection guidelines. The ambient temperature for the day can be seen in Figure 46 below. The wind speed was 5-9 mph for most of the day. There were short periods of wind speeds at 13 mph. The ambient temperature change was greater than 15 degrees for the day and was also more than 10 degrees in the first six hours after sunrise.

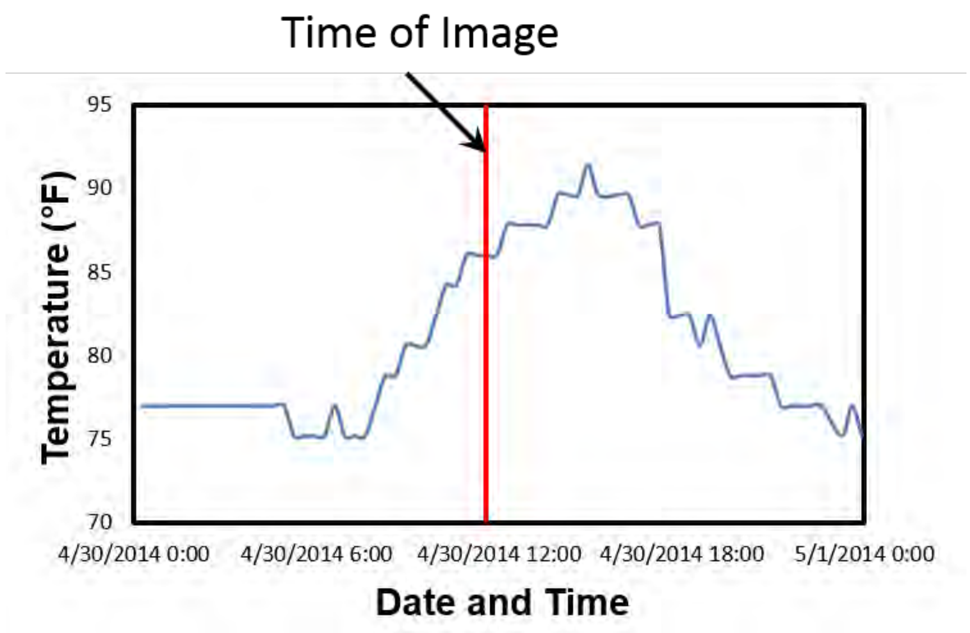


Figure 46: Ambient temperature on April 30, 2014 for Tampa, FL

11 OHIO

A wide bridge located at I-70 over Glenwood Avenue was inspected June 23, 2014 in Columbus. Members of Ohio Department of Transportation had been having some issues with getting good infrared results on a wide bridge (greater than 100 ft.). This was the first time this issue had been brought to attention. The Glenwood Avenue

Bridge was selected as a testing site so as to determine if wide bridges could provide enough ambient temperature change underneath to allow for good infrared inspection results. Two other bridges were also inspected on the Ohio trip; their images can be seen on the pooled fund project website.

Images from the Glenwood Avenue Bridge were captured both in the morning and the afternoon. The morning images were captured between 7:30 A.M. and 8:15 A.M when the thermal contrast started to disappear. The afternoon images were captured between 2:45 P.M. and 3:00 P.M. By capturing images in both the morning and the afternoon, there is an opportunity to show how delaminations appear differently during different times of the day. An example of the difference in thermal images can be seen in Figures 47 and 48. The images aren't in the same location but Figure 48 shows images located near the center of the width.

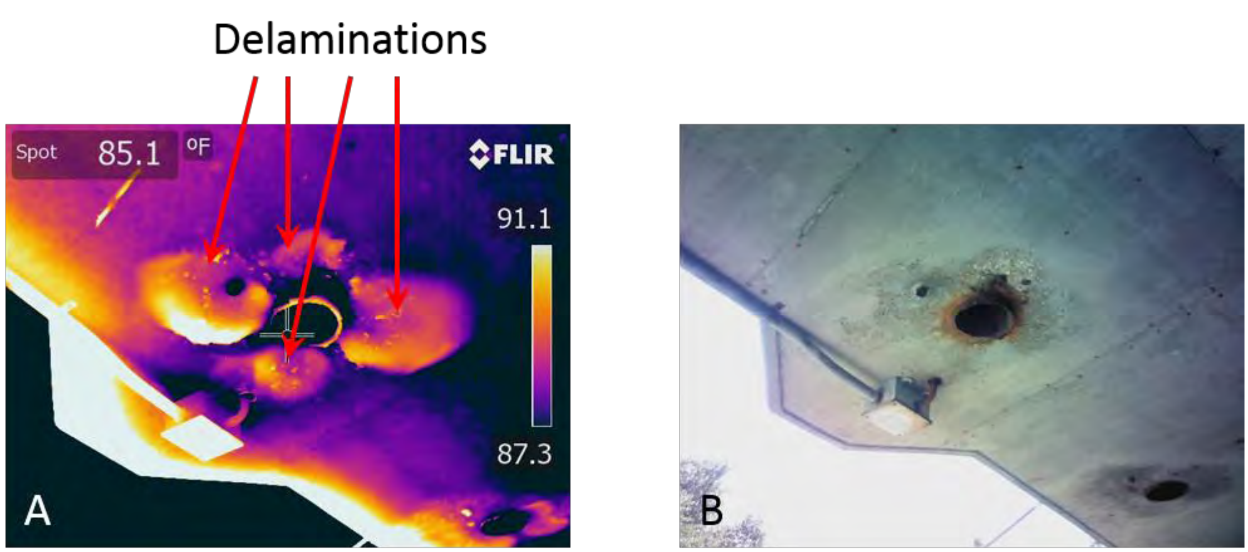


Figure 47: Afternoon infrared (A) and digital (B) images of a soffit delamination in Columbus, Ohio

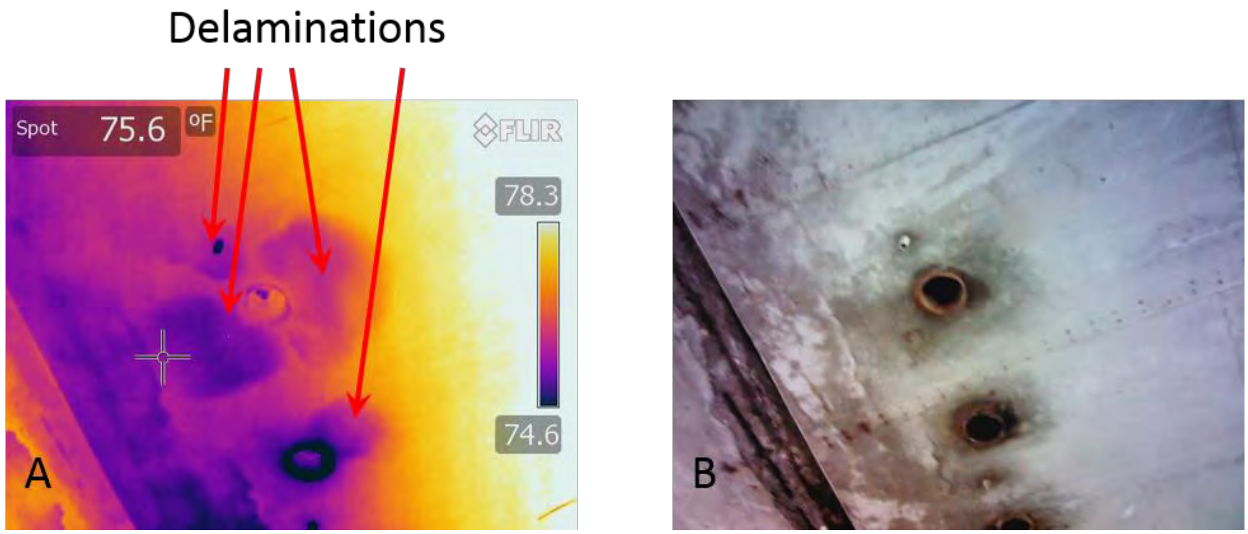


Figure 48: Morning infrared (A) and digital (B) images of a soffit delamination in Columbus, Ohio

Another example in Figure 49 shows delamination surrounding a scupper in the soffit of the bridge. The figure shows the same area of the bridge, during the morning and during the afternoon. As shown in the images, the delaminations appear as cold spots during the morning hours, and as hot spots during the afternoon.

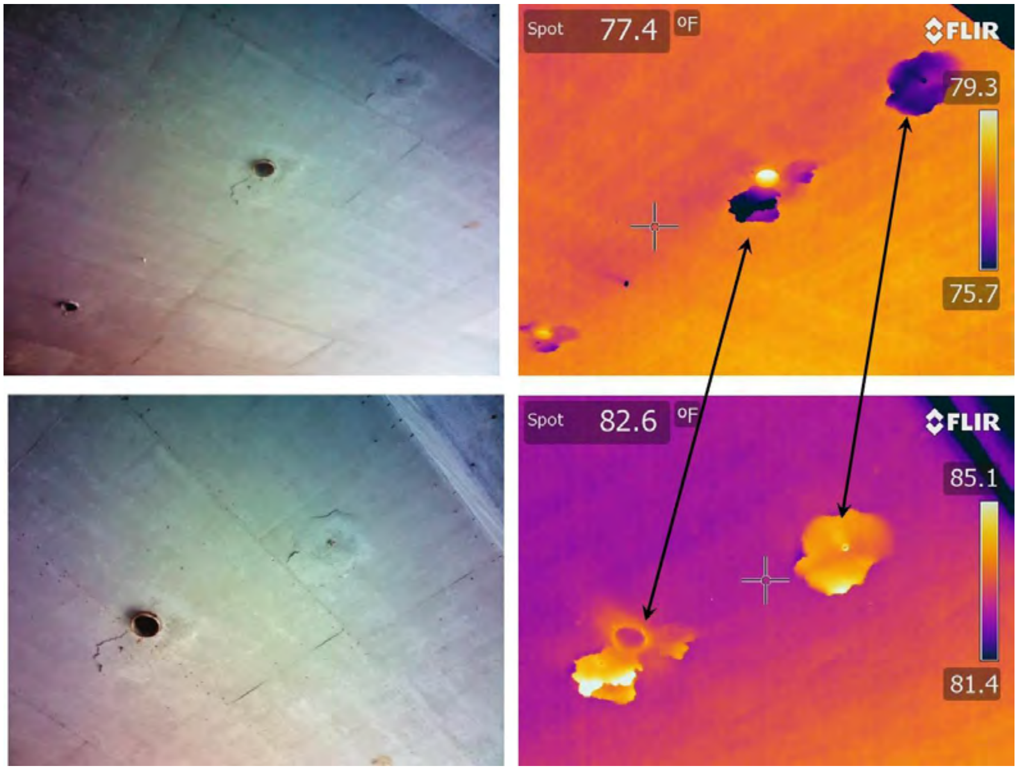


Figure 49: Thermal images of delaminations in the soffit of a wide slab bridge, showing morning (top) and afternoon (bottom) results

Images were also captured showing damage surrounding a longitudinal joint at the center of the bridge. Again, images are shown from the morning and the afternoon. As shown in Figure 50, damage surrounding the longitudinal joint could be imaged both in the morning and in the afternoon.

Figure 50: Thermal images showing damage along a longitudinal joint in a 159 ft. wide slab bridge

The weather conditions for the day indicated a successful day for infrared inspection. The ambient temperature for the day can be seen in Figure 51 below. The times marked on the graph indicate the times of day Figures 49 and 50 were captured. The wind speed was consistently below the 15 mph threshold provided in the guidelines.

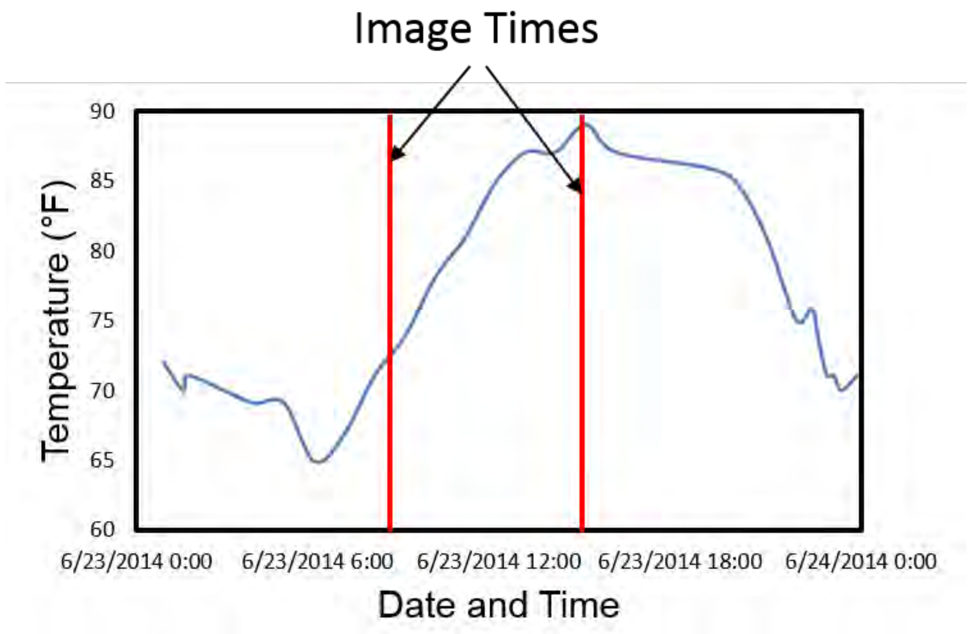


Figure 51: Ambient temperature for June 23, 2014 in Columbus Ohio

It was concluded that, with sufficient weather conditions, wide bridges would not be a problem for inspection using infrared thermography. These conclusions were drawn from the image quality during both the morning and afternoon images. The images were comparable to soffit images from other bridges under similar weather conditions.

REFERENCES

Nelson, Seth (2013) “Field Testing Hand-Held Thermographic Inspection Technologies Phase II” Master’s Thesis, University of Missouri, Columbia, MO

Wiss, Janney, Elstner Associates, Inc. (2013) “Specialized Post-Tensioning Void Testing”. Seattle, WA.

Wunderground (2014) Archived weather history. Accessed numerous times from 2012-2014. Retrieved from http://www.wunderground.com/history/.

Presentations from the Training

Appendix D

University of Missouri

Columbia, MO

October, 2014

Appendix

Training Modules

Thermography Module 1, Introduction

Iowa Department of TRANSPORTATION
OREGON.gov
Oregon Department of Transportation
pennsylvania
Wisconsin Department of Transportation
Texas Department of Transportation
Minnesota Department of Transportation
MDOT
New York State Department of Transportation
MoDOT Missouri Department of Transportation

1

Overview of Training

- Day 1
  - 8-11 classroom discussion
  - 11-12 lunch
  - 12-2 travel to bridge site
  - 2-4 use IR camera to image in PM conditions
  - 4-5 return
- Day 2
  - 8-10 discussion of yesterday's imaging
  - 10-11 travel to same bridge site
  - 11-12 use IR camera to image in AM
  - 12-1 return

The Objectives of this project:

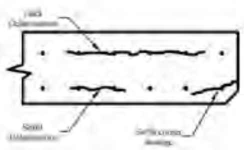
- Using new cameras, test operational parameters with DOT personnel on actual bridge inspections
  - Collect data and upload results to a database
  - Conduct periodic interviews to determine improvements / modifications in use procedures to optimize value
  - Disseminate findings among participating states on an on-going basis
- In parallel with field operations, conduct verification testing, modify the guidelines and conduct lab investigations
- Analyze field data, integrate lab data, and develop a recommended practice that instructs DOT personnel on how to best apply the cameras in the field

Desired results of this project

- Provide maintenance and inspection personnel with a tool for condition assessment of concrete bridges
  - Does not require access
  - Does not disrupt traffic
- Improve their ability to identify defects and deterioration
- Improve the ability to identify the extent of damage to decks w/o interrupting traffic

Background

- Corrosion of embedded reinforcing steel leads to delaminations and spalling of concrete
  - When steel converts to iron-oxides, the corrosion product has greater volume than the steel
  - Tensile stresses resulting from the expansion, which is confined in the concrete, leads to cracking of the concrete
  - Cracks join to form delaminations; grow to surface and cause spalling



Example Bridge Deck Delamination

Detecting Delaminations in Concrete

- Hammer sounding is the standard for detecting spalling concrete, but
  - requires hands-on access to the surface of the structure which usually requires traffic control
  - Results are relatively subjective
  - Time consuming
- Infrared cameras
  - can image areas without hands-on access and at greater distances
  - can quickly determine the extent of delamination
  - images can be viewed and interpreted in the field <u>and</u> transmitted and archived at the office
  - Results document in digital file
  - More objective (?)

IR Challenges

- IR is capable of detecting delaminated concrete
  - Environmental factors limit the reliability and capability of the technology
- These factors include
  - Wind speed, solar radiation, diurnal temperature variations, shade, observation angle, reflections from environment, color variations, precipitation
  - Depth of delamination, type of overlay, etc.

How does it work?

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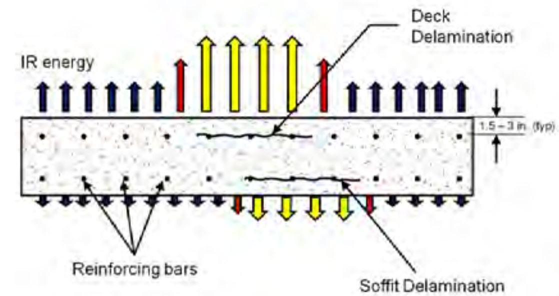
IR Emitted From Concrete Bridge Decks



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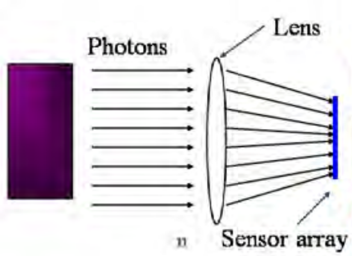
IR cameras are similar to ordinary digital cameras

- Infrared cameras and digital cameras both use charged couple devices (semiconductors) to measure the number of photons impinging on the target array inside the camera
- The target semiconductor is tuned to the appropriate wavelength



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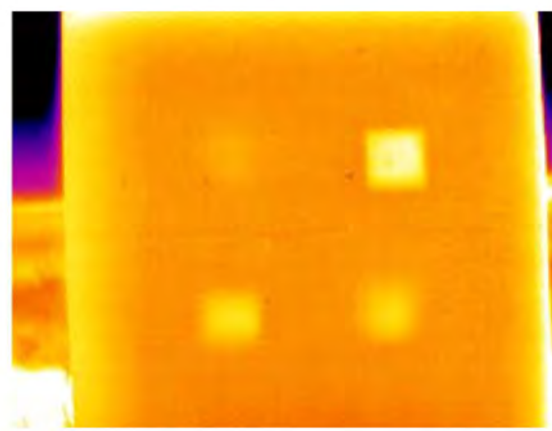
Phase I Research Background



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Experimental Background

- Field
  - Thermal contrast was measured in a test block at different void depths, with and without solar loading, and at a variety of temperature, wind, and humidity conditions to determine the parameters for good thermal imaging. Those findings are the 'Guidelines'
- Lab
  - COMSOL software was then used to create a data model, (calibrated against field data)

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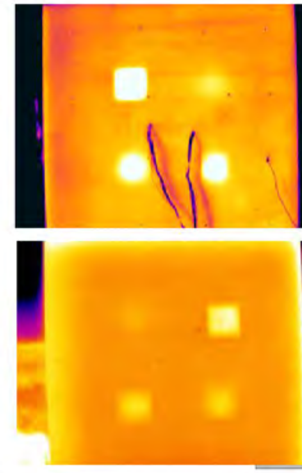
Test Block



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As part of the experimental background to this project, draft use guidelines were developed

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Phase II: Implementing

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Training Objectives

- Theoretical background of thermography
- Experimental background of this project
- How to make a good IR image
- Using the FLIR T620 camera and software

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During today's training…

- Discuss the your thermography experience to date
- Discuss the theoretical and experimental foundations of this project
- Familiarize you with the FLIR T620 camera
- Familiarize you with good IR imaging practices
- Discuss IR image interpretation and data management
- Deliver FLIR camera for your use

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FLIR T620 Thermal Camera

- Hardened for field use
- Good digital camera
- Higher resolution imager
- Good battery life
- Also looked into Jenoptik and Fluke IR cameras
  - good systems but FLIR offered better features for field use

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Thermography

Module 2, Theoretical Background: heat transfer

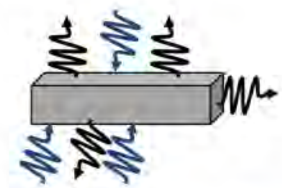
Iowa Department of Transportation
Minnesota Department of Transportation
MDOT Department of Transportation
New York State Department of Transportation
Missouri Department of Transportation
pennsylvania
Wisconsin Department of Transportation
OREGON.gov
Oregon Department of Transportation
Texas Department of Transportation
GDOT Georgia Department of Transportation

This module's agenda

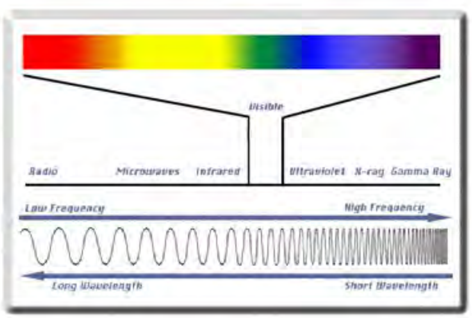
- What is infrared thermography?
- Heat Transfer
  - Convection, Radiation, Conduction
- Factors affecting IR cameras
  - Thermal emissivity
  - Object shape and corner effects
  - Surface (texture, water, asphalt, etc.)
- Review

IR Radiation

- Materials/Objects
  - Emit radiation into the environment
  - Absorb radiation from the environment
  - At thermal equilibrium, emit and absorb at the same rate



What is Infrared Radiation?



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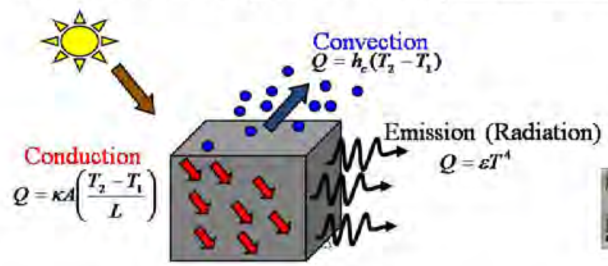
Thermal measurements

- Heat flows (transfers) from hot to cold
- Thermography measures IR radiation emitted from an object, and creates an image in which different colors represent different temperatures
- Reflections, an object's shape and its internal features affect the amount of IR radiation it emits
- Amount of emitted radiation proportional to T^4

3 fundamental methods of heat transfer

- Wind over hot concrete cools it by *convection*
- Direct sunshine on concrete heats it by *radiation*
- Heat flows through concrete by *conduction*



Convection

- Examples of heat transfer by convection
  - Wind blowing over a concrete bridge deck
  - Fan blowing air over a concrete test block
- If concrete is warmer than environment (solar), wind is detrimental
- If concrete is cooler, wind can be helpful

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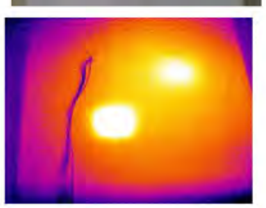
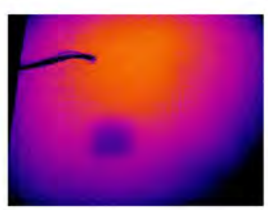
Convective cooling reduces thermal contrast

- Air blowing over a heated block of concrete cools it by convection





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Conduction

- Heat transfer by contact
- Internal heat transfer in solids
- Affected by:
  - Thermal conductivity of material
  - Distance (Time)
  - Temperature gradient

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Conduction

- The sun heats one side of the bridge
- The heat flows through the steel
- But this flow takes time, providing a temporary temperature difference (thermal gradient)

$$Q = \kappa A\left(\frac{T_2 - T_1}{L}\right)$$

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Radiation

- Radiation is the transfer of heat by electromagnetic waves
- Radiation from the sun heats things on earth
  - Direct radiant heating on decks
  - Objects radiate IR energy
    - Detected by camera

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Thermal Inertia

- Thermal inertia is a measure of a material's ability to conduct and store heat
- Is a function of: k = thermal conductivity, ρ = density, C = specific heat
- Materials tend to:
  - Retain previous temperatures
  - React slowly to thermal changes

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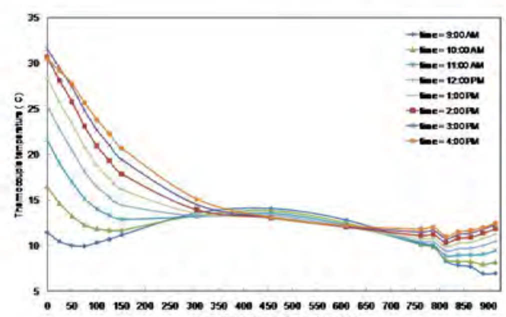
Test Block



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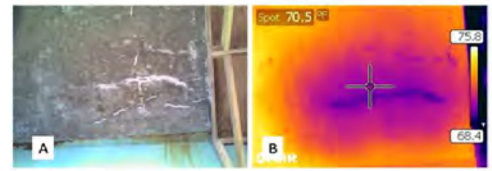
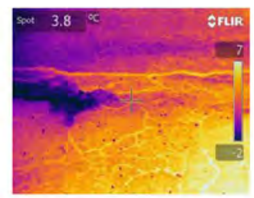
Thermal images are affected by

- Edge Effects
  - Edges and corners heat first
- Moisture
  - Wet spots have different thermal inertia and may have different emissivity
- Internal Features
  - Internal features such as diaphragms, voids, etc. show through in thermal images

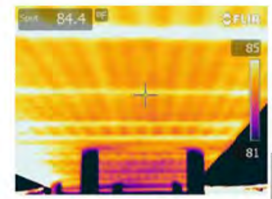
Examples



Saturated



Surface Cracks



Internal Diaphragms

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Examples

Corner Effect

Emissivity Difference

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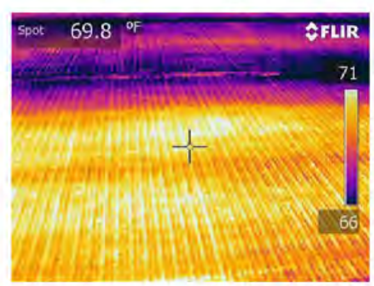
The angle of observation affects the apparent amount of thermal emission

- More energy is emitted at normal angles



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Summary

- 3 types of heat transfer
  - Convection, Conduction, Radiation
  - IR cameras image surface temp
- Thermal Inertia
- Infrared Radiation
- Factors affecting images
  - Edge effects
  - Angle
  - Surface cracks

Thermography

Module 3, Environmental Factors affecting IR images

This module will describe:

- Environmental effects on image quality
- Experimental findings from phase I
- Examples of good and bad conditions for capturing thermal images based on:
  - Ambient temperature
  - Solar loading
  - Wind speed
- example thermal images of delaminations with and without solar loading

Experimental Findings

- For solar exposed surfaces:
  - Late afternoon provides optimum thermal contrast, so imaging is best and deepest voids can be detected
  - Low wind speed improve thermal imaging
- For non-solar exposed surfaces
  - The part of the day in which ambient temperature is increasing is best for imaging
  - Moderate wind improve thermal imaging due to convection heating or cooling

Experimental Setup

- A concrete test block with embedded Styrofoam blocks and thermocouples was constructed to simulated a concrete bridge with voids
- An on-site mini-weather station was assembled to monitor:
  - Ambient Temperature
  - Solar loading
  - Wind Speed
  - Humidity
- Data was logged every 10 minutes, 24 hours a day

Simulated subsurface Defects

Test Block Construction

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Test Block – Data House

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Test Block, Weather Station, and Monitoring Equipment

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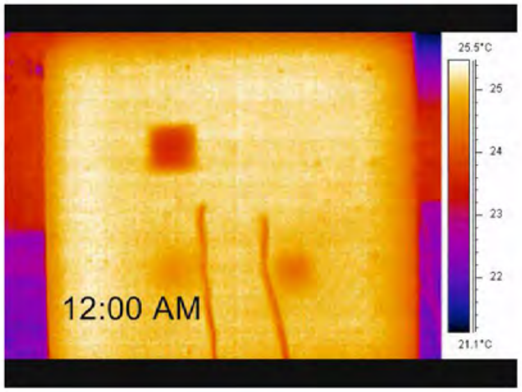
24 hour Test Block Video



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Other Effects

- Time delay from application of heat to detection of damage

$$t \sim \frac{z^2}{\alpha}$$

t = observation time (s)
z = depth of the target (m)
α = thermal diffusivity of the material
K = Thermal Conductivity
C = Specific Heat

$$\alpha = \frac{K}{\rho C}$$

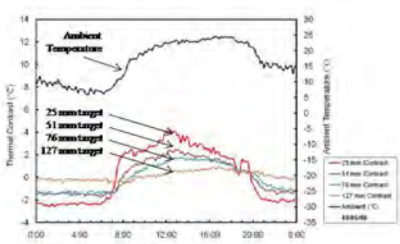
- Contrast loss is a function of defect depth

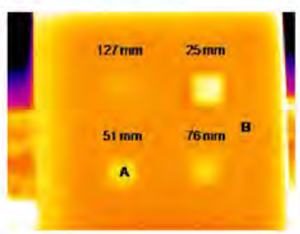
$$c \sim \frac{1}{z^3}$$

c = thermal contrast loss due to defect depth
z = depth of the target (m)

Data Reduction with application

- Graph on left has 2 (y) axis
  - On LHS, the thermal contrast between a pixel over a target and a pixel in acreage
  - On RHS, environmental variable is shown
    - Ambient temperature, solar loading, wind speed, or humidity





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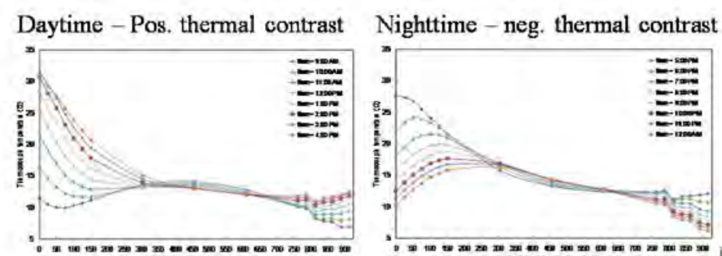
Thermal Gradient in Test Block



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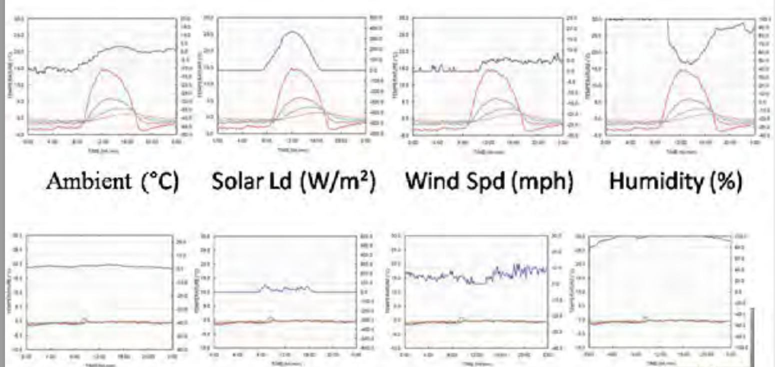
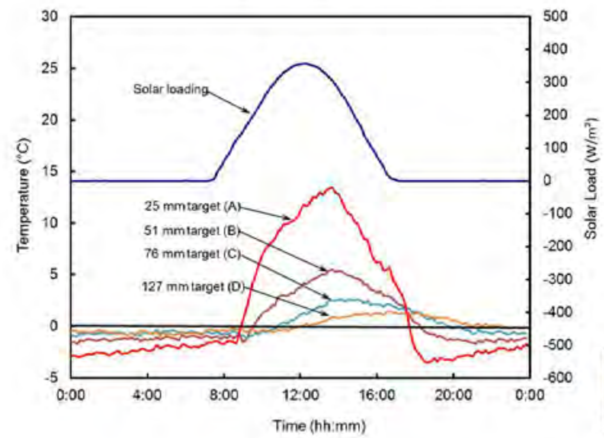
Ambient temperature vs. thermal contrast: good conditions for thermal imaging (12/17/07) and poor conditions for thermal imaging (1/10/08)



12

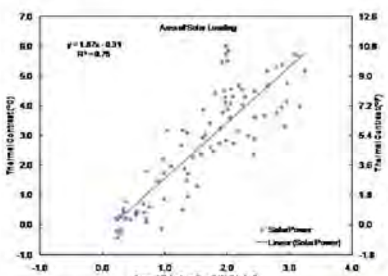
Solar Loaded



Results – South Side

Effect of Solar Loaded

Area of Solar loading:
Intensity of sun x time
-For 1 °C contrast, 0.7 kW-hr/m²
Min.



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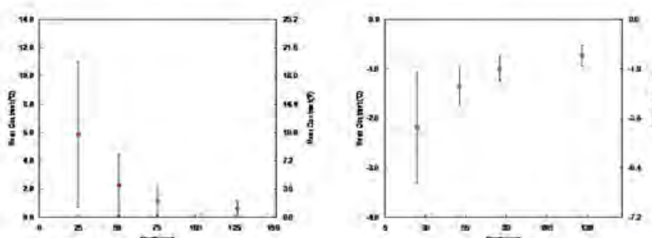
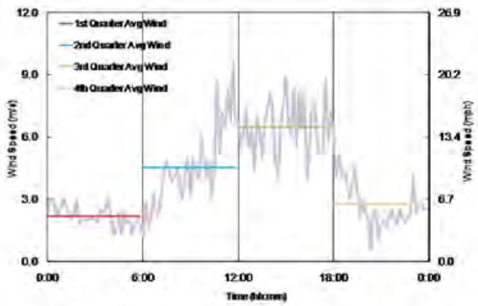
Effect of Depth of Target

- Month of November, South Side



Average Wind Speeds - Quarters



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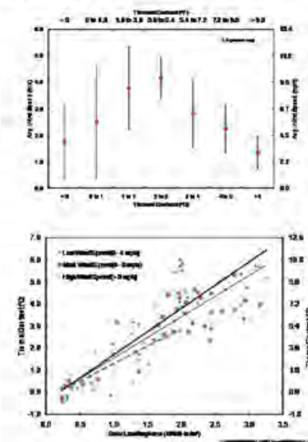
Effect of Wind, South Side

- For the sunny (south) side, low winds are characteristic of days with high contrast
- Trend of wind speed (lower figure) shows that winds are detrimental
  - Under solar loading, the wind cools the concrete (which is warmer than the ambient environment) and as such reduces the effect of the sun (reduces contrast for defects)
  - Note: Long dashed lines = high wind speeds, short dashed lines = low wind speed



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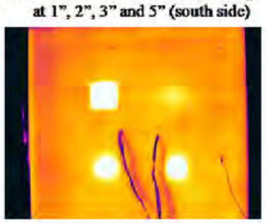
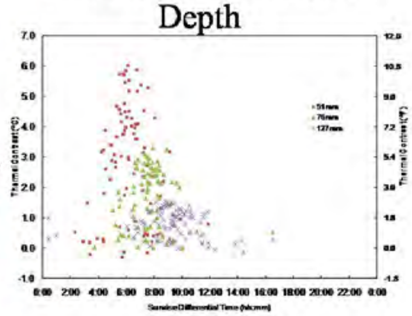
Effect of Delamination Depth

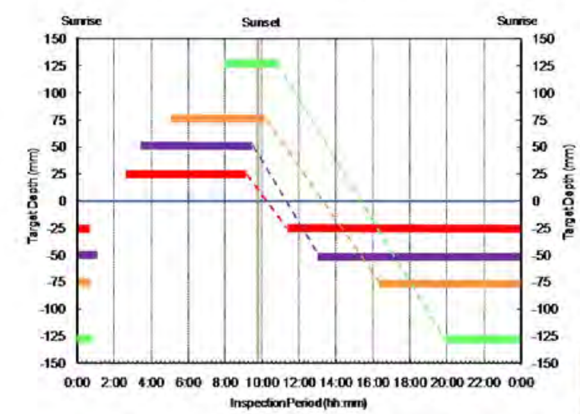
Reinforced concrete block with targets at 1", 2", 3" and 5" (south side)





Plot of image contrast maximums vs. time of day (3 months of data) (direct solar loading)

Inspection Periods – South Side



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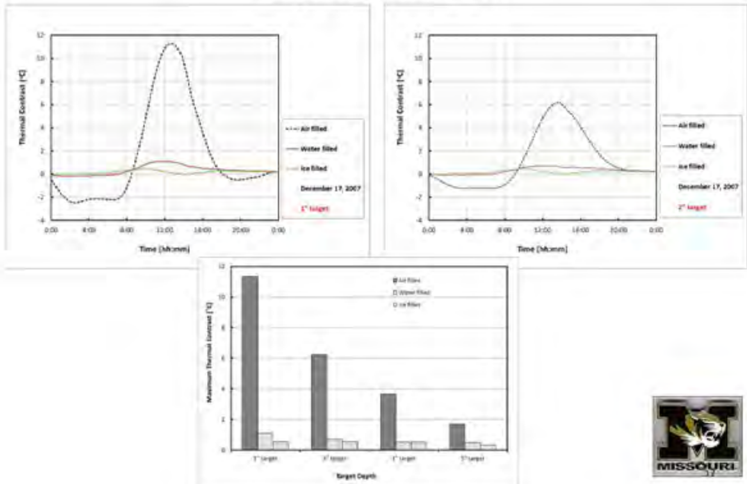
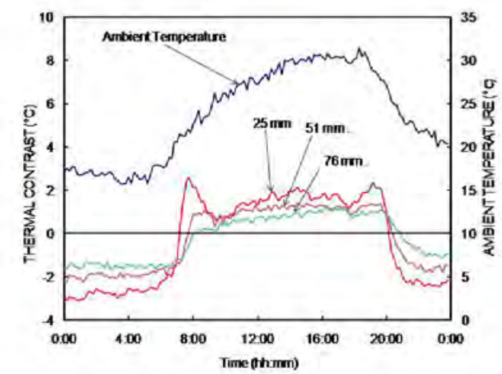
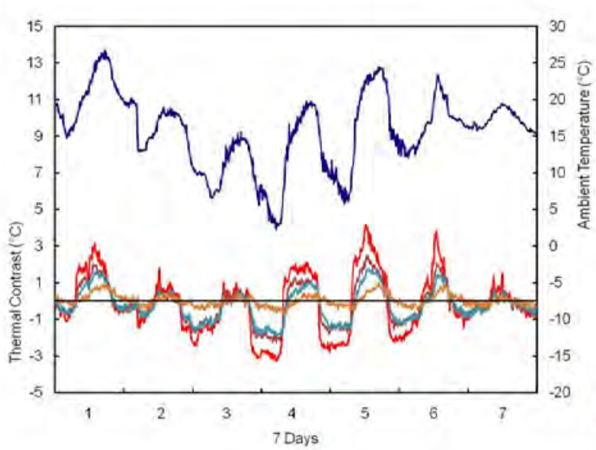
Filled Defects



Shady Conditions

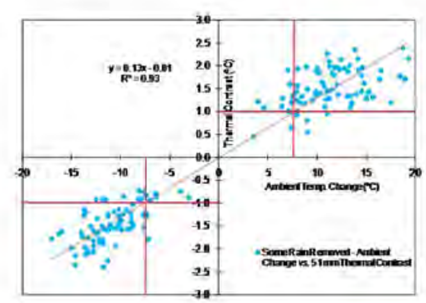


Ambient Temperature vs. Thermal Contrast (North side)

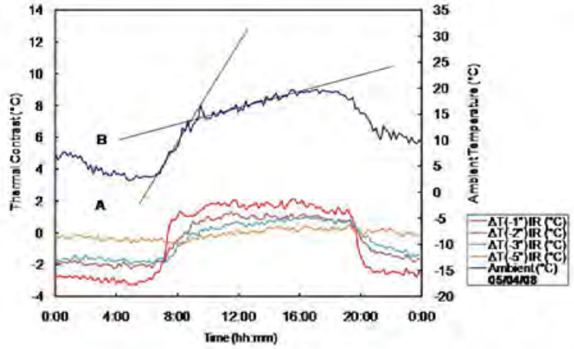


Ambient Temperature Change vs. Thermal Contrast

- On average, 1.4 ºC of contrast either positive (day) or negative (night)



Rate of Change Analysis (ROC)



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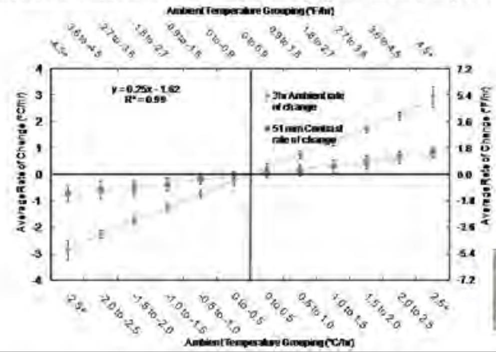
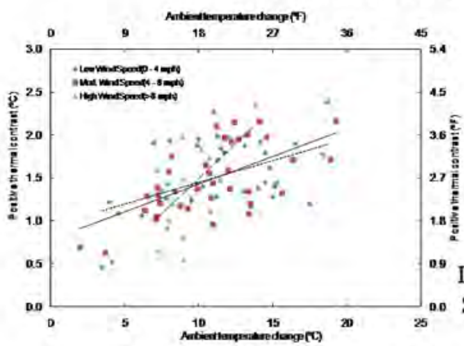
Ambient ROC, 2 in. Deep Target

- It was found that contrast is diminishing when ROC < 0.5 deg C/hr
  - During times of constant temperature, contrast is diminishing, avoid inspections during this time for 2 in. deep defects
  - Inspection should be done during changing ambient temperature

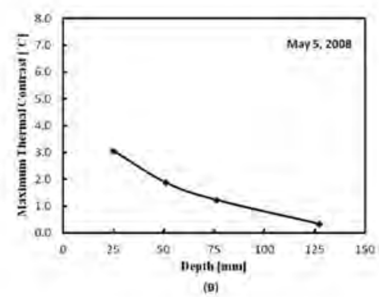


Effect of Wind
North Side

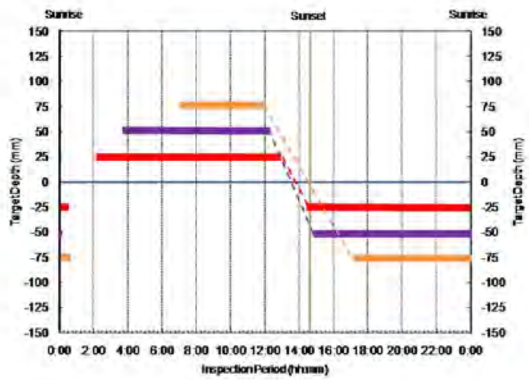


Long dash line = high wind
Short dash line = low wind

Effect of Depth
North Side



Inspection Period – North Side



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Guidelines Overview

- For solar exposed surface
  - 4 hrs. after sunrise (2 in. deep). For 3" deep defect, 5-6 hrs. after sunrise, will last about 5 hrs.
  - Less than average 8 mph winds
- Shaded side
  - Temperature difference of 15° F
  - 10 degrees in first 6 hours after sunrise
  - When temp. decreases, contrast begins to decrease
  - At least 4 hrs. after sunrise for 2 in., about 7 hrs. for 3 in. deep flaws
  - Wind speed less than average 10 mph (?)
    - Wind not necessarily bad

Review

- Experimental set up
- Good vs. bad days for making thermal images
- Delaminations with and without solar loading
  - For solar exposed surfaces
    - Low wind speed and low humidity
    - Late afternoon provides optimum thermal contrast
  - For non-solar exposed surfaces
    - Moderate wind improve IR imaging (?)
    - Part of the day when the ambient temperature is increasing
      - Morning

Thermography
Module 4, Making a Good Image

Iowa Department of TRANSPORTATION
OREGON.gov
Oregon Department of Transportation
pennsylvania
Wisconsin Department of Transportation
Texas Department of Transportation
Minnesota Department of Transportation
MDOT
New York State Department of Transportation
Missouri Department of Transportation

68

This module's agenda

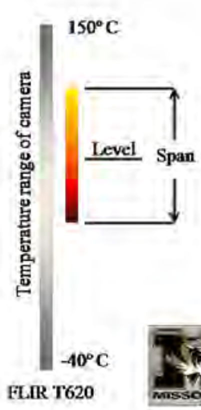
- Capturing a good image
  - Level and Span
  - Image Parameters
    - Focus
    - Range
    - Composition
- Thermal Tuning
- Lens selection

Level and Span

- The *level* is the temperature at the center of the *span*
- The *span* is the temperature range over which the color palette is applied
  - *Palettes can be altered*
  - *Temperature ranges outside the span are shown as the limit color in the span*

Level and Span

- The span moves with the level across the cameras range
- Span enhances the contrast in the image



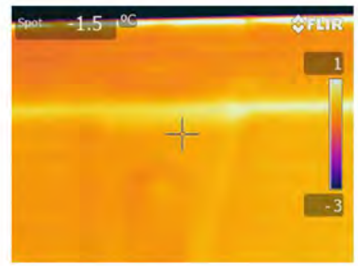
Level and Span

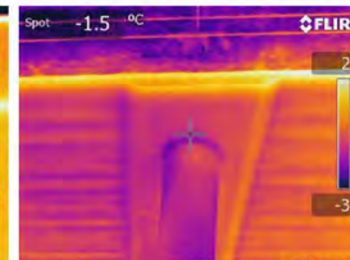
- For concrete structures, typical span settings are in the range of 2 to 8 degrees C.
- The span level setting is critical to allowing for contrast in the image

Focus

- Thermal cameras focus is much the same way as any other camera
- Focus cannot be adjusted once an image has been saved on the camera
- The focus varies according to range, and may need to be adjusted frequently if the range to the object under inspection varies
- Use an edge, tool or coin to enable focus
  - Some defined edges in the thermal image

Focus importance for object clarification



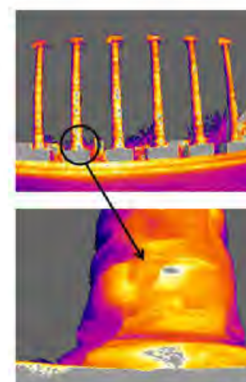


Composition

- Images are created by a focal plane array in the thermal camera
- Each pixel corresponds to a physical size
  - The greater the range to the target, the larger the physical space imaged by each pixel in the camera
- At large distances, small features are lost
  - Zoom in camera is digital (pixels just become larger)

Composition

- From large distances, area of thermal contrast may consist of only a few pixels
- Imaging with the correct composition allow for the boundaries to be defined



Thermal Tuning

- Adjusting image to enhance the contrast
- Level adjustment
  - Bring middle of span to an average temperature for the structure being observed
- Span Adjustment
  - Create the contrast needed to identify thermal anomalies

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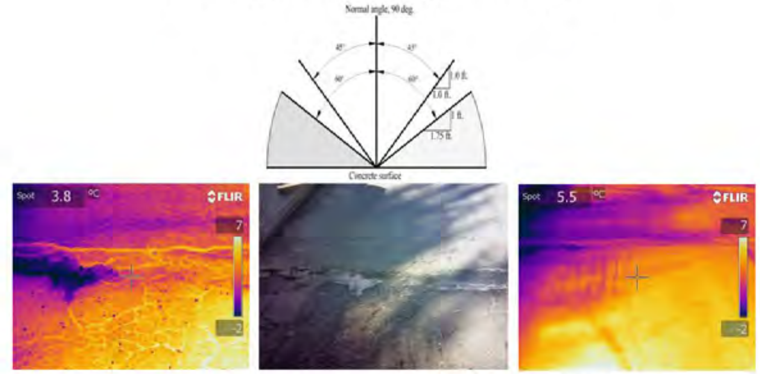
Using the Proper Angle



Good Angle

Bad Angle

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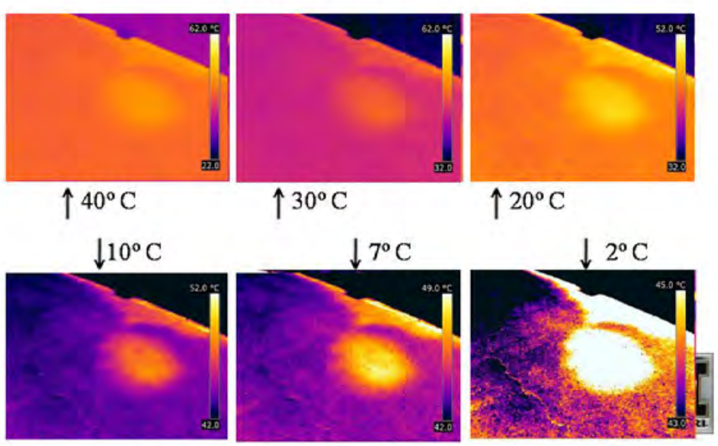
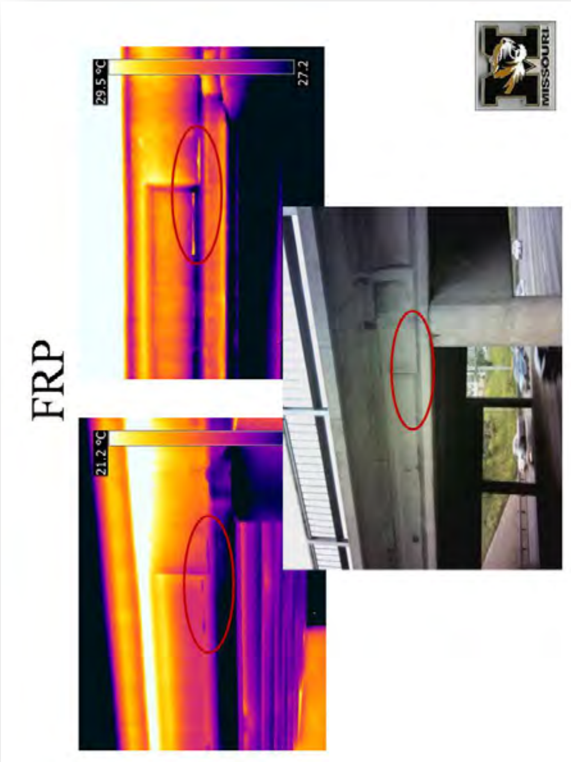
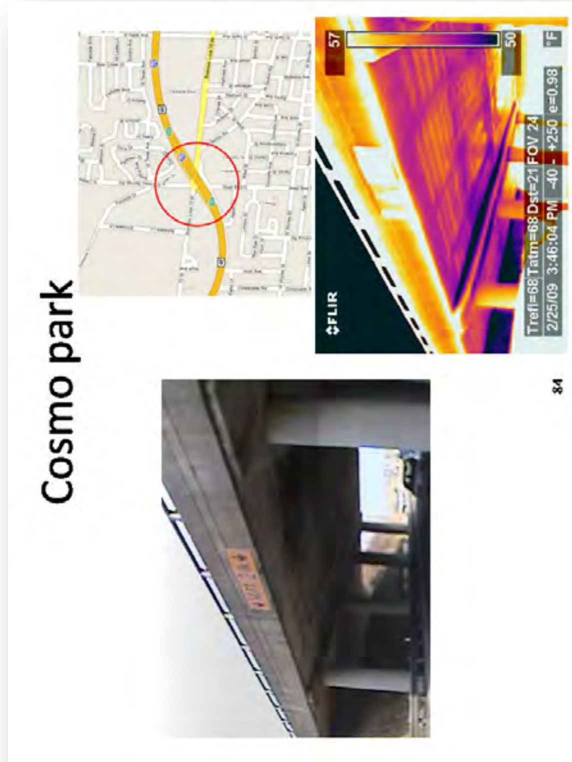
Perfecting the Manual Span/Level Adjustment

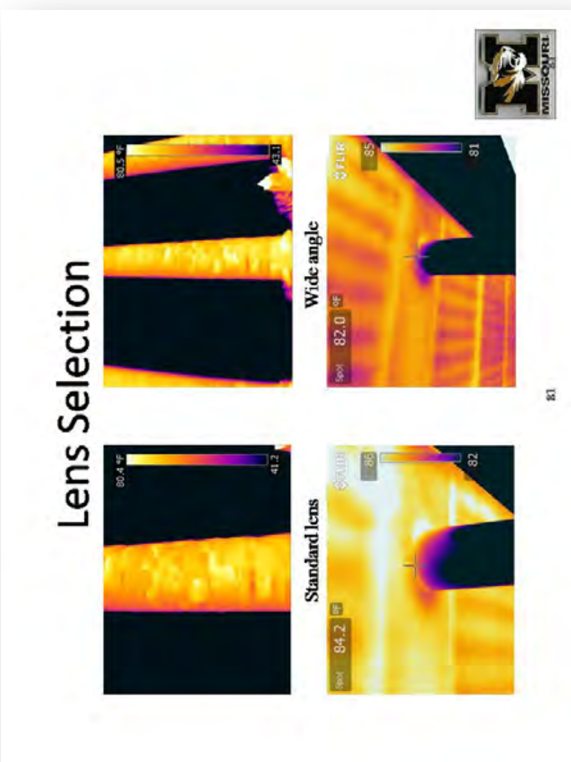


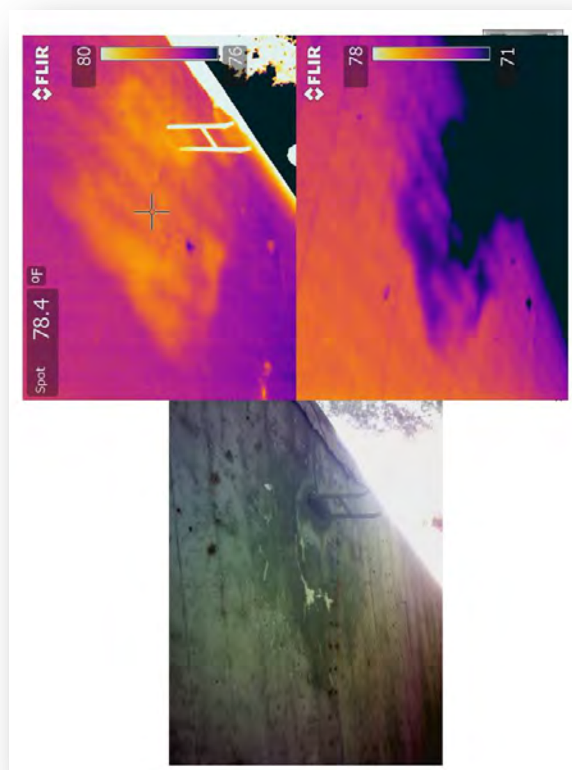
Lens Selection

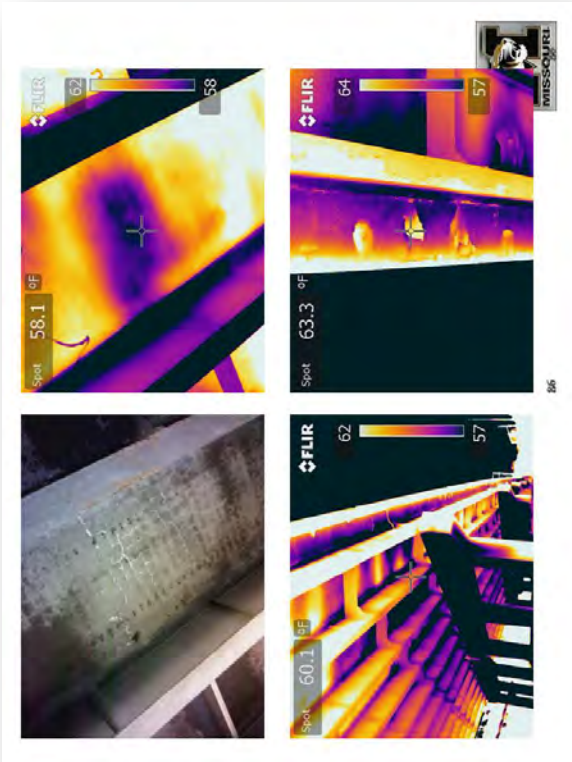
- Camera has two lenses –
  - 25 º
  - and wide-angle, 45 º
- To compose an effective picture, adequate image content is required to detect areas of thermal variation
  - If close to a bridge, thermal variations may not appear if larger than imaging space

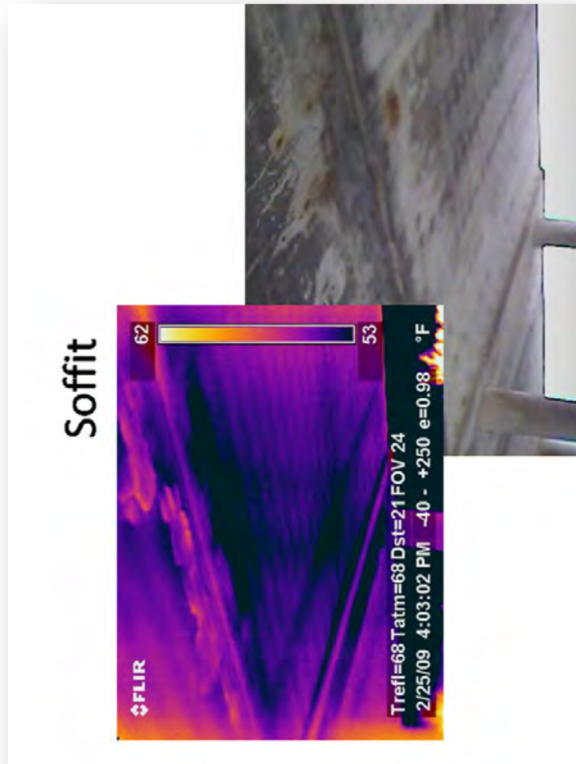

FRP
29.5 °C
27.2
21.2 °C
MISSOURI

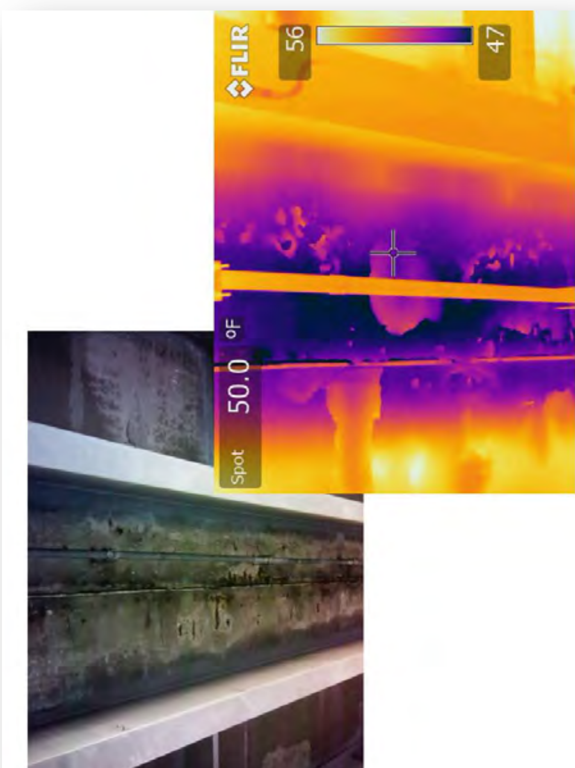

Cosmo park
FLIR
57
50
°F
Trefl=68 Tatm=68 Dst=21 FOV 24
2/25/09 3:46:04 PM -40 - +250 e=0.98
84

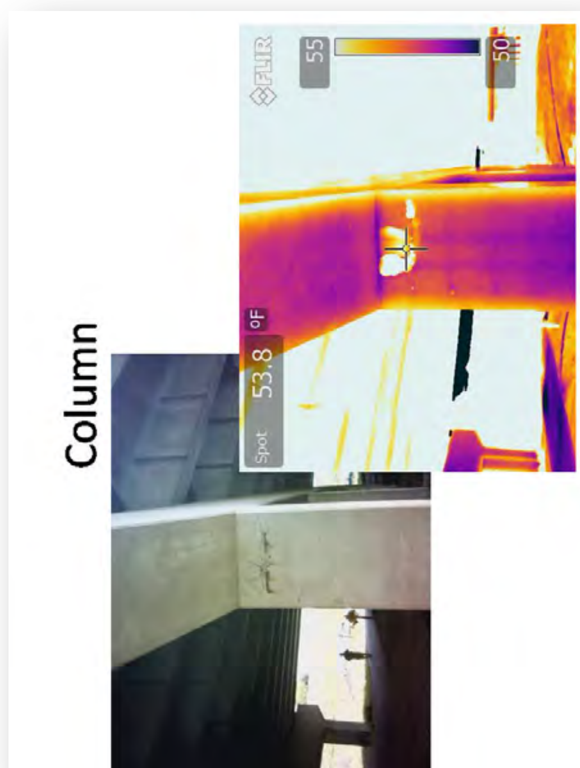

Lens Selection
80.4 °F
41.2
80.5 °F
43.1
Standard lens
Spot 84.2 °F
86
82
Wide angle
Spot 82.0 °F
85
81
MISSOURI

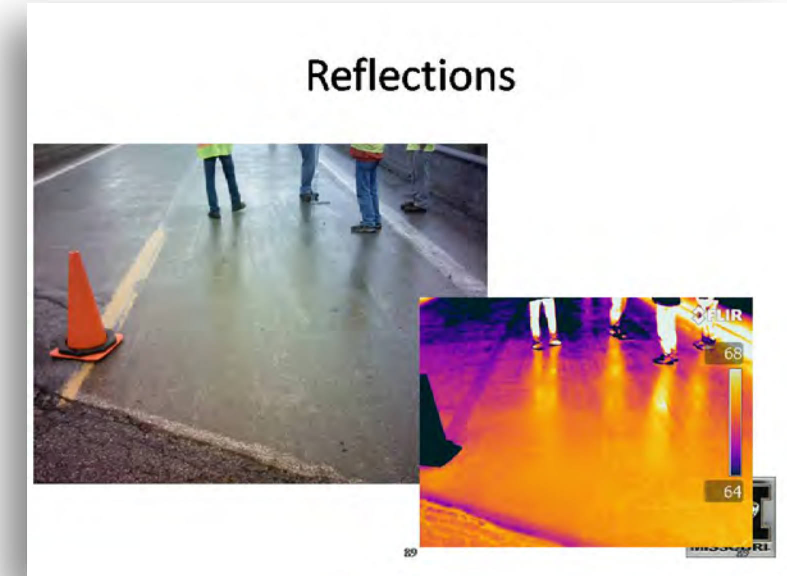

FLIR
80
76
Spot 78.4 °F
FLIR
78
71


FLIR
Spot 58.1 °F
62
58
Spot 60.1 °F
Spot 63.3 °F
64
57
MISSOURI


Soffit
FLIR
62
53
Trefl=68 Tatm=68 Dst=21 FOV 24
2/25/09 4:03:02 PM -40 - +250 e=0.98 °F

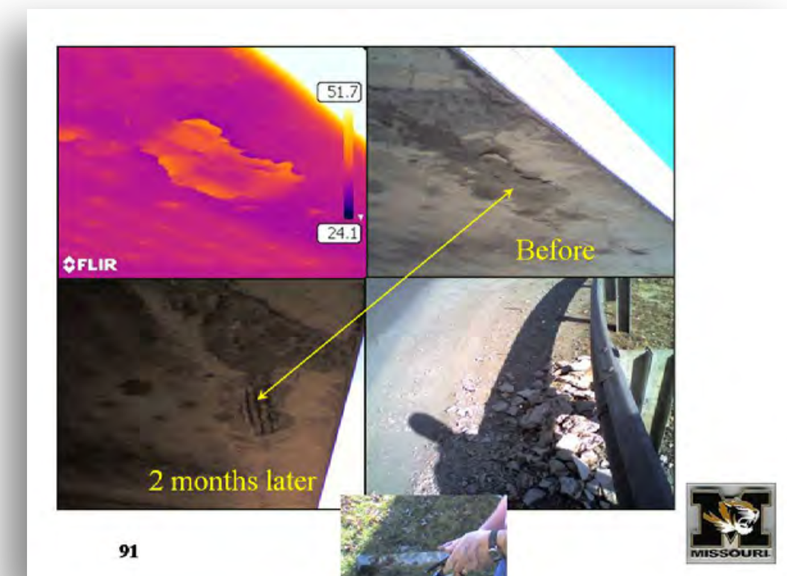

FLIR
Spot 50.0 °F
56
47


Column
FLIR
Spot 53.8 °F
55
50

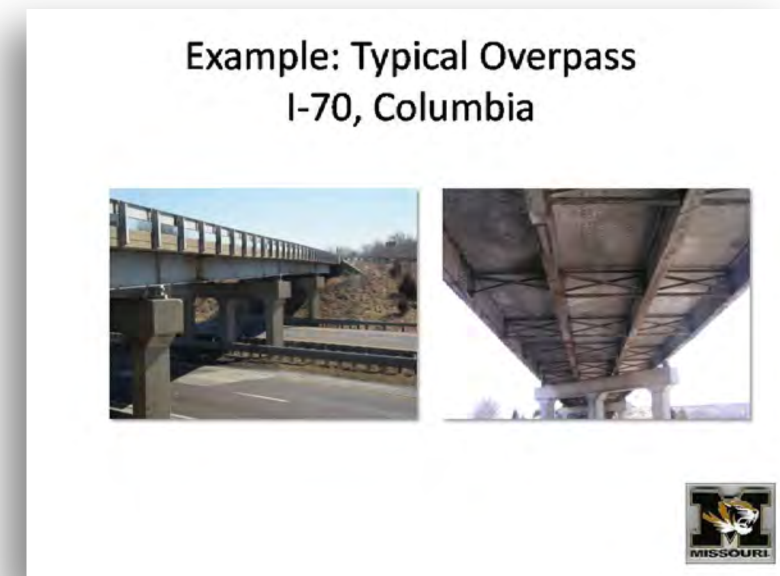


Reflections
FLIR
68
64
89

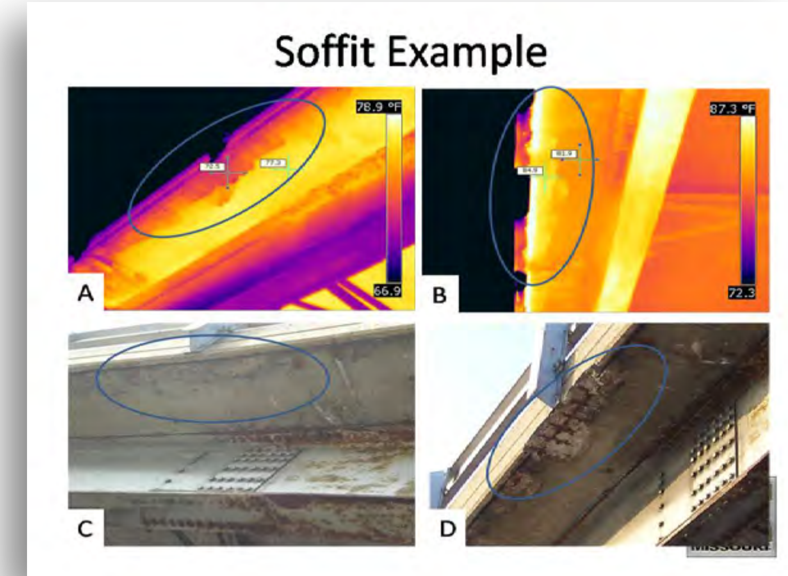
FLIR
81
49



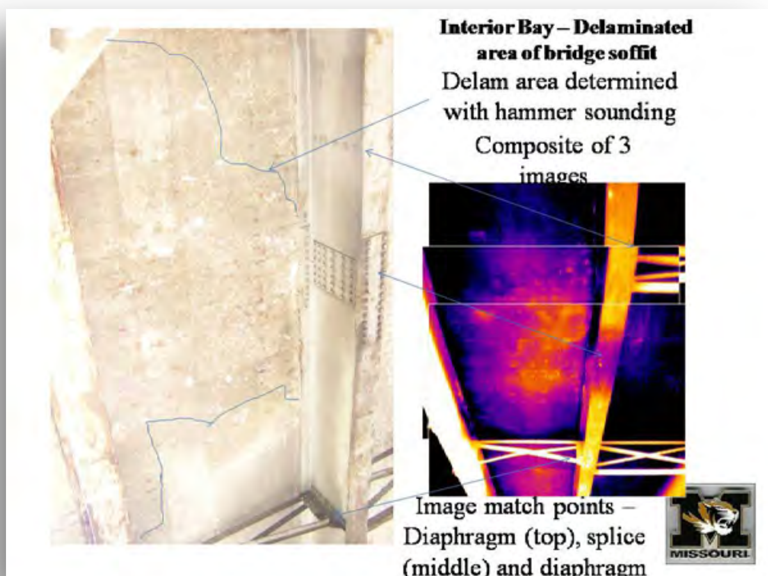
51.7
24.1
FLIR
Before
2 months later
91
MISSOURI

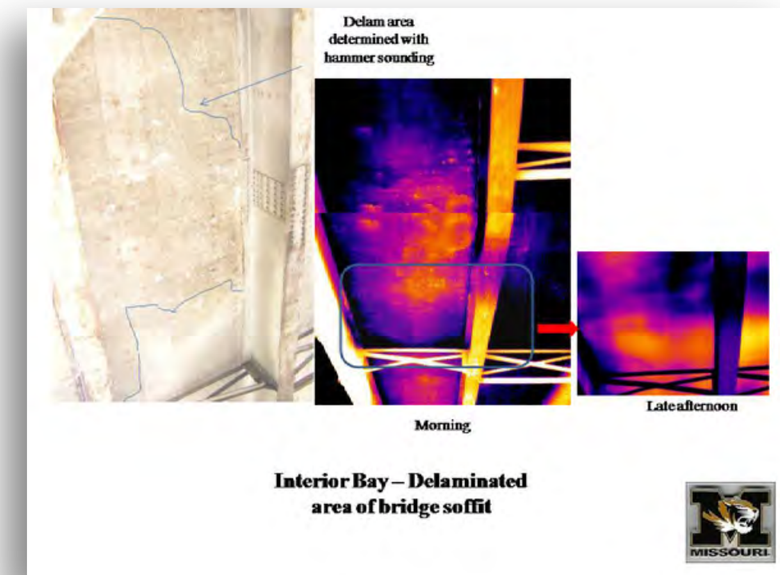


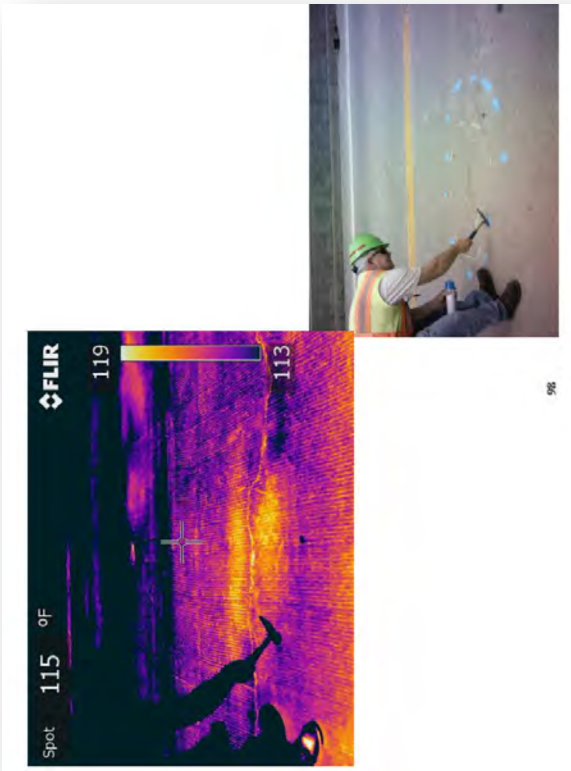
Example: Typical Overpass
I-70, Columbia
MISSOURI

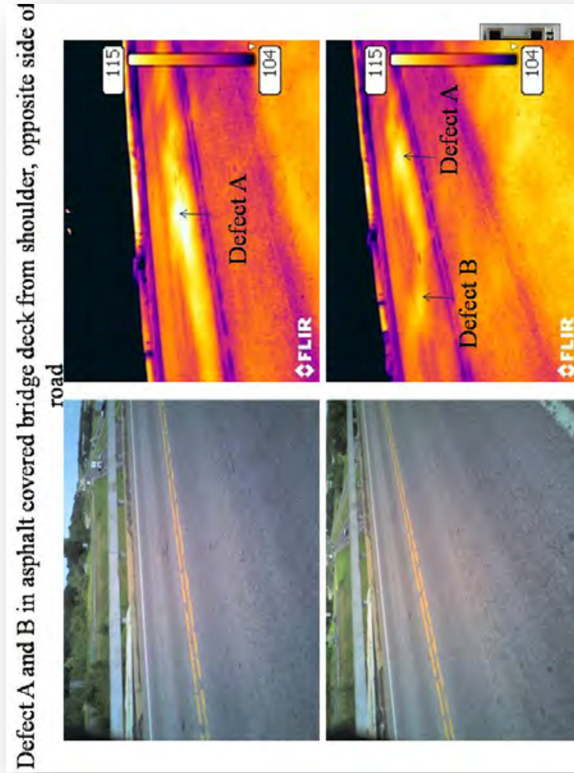

Soffit Example
78.9 °F
66.9
A
87.3 °F
72.3
B
C
D

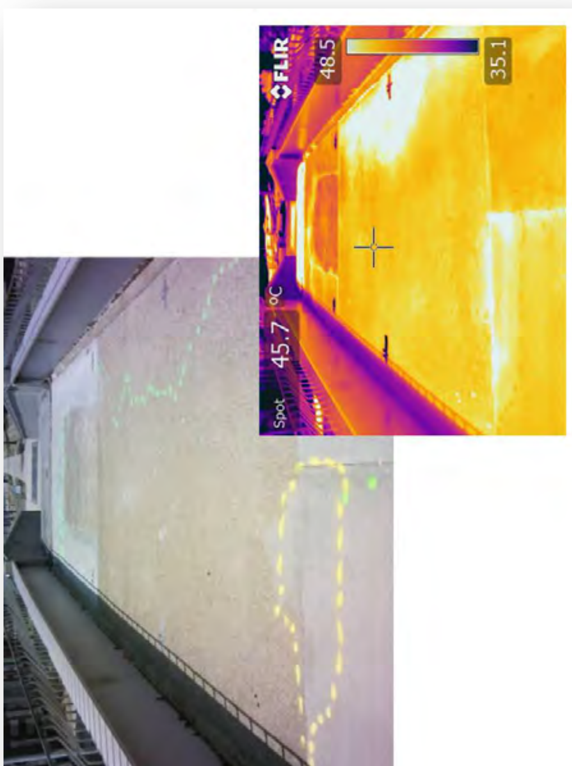

Video of IR Inspection
Before
78.5 °F
66.5
MISSOURI

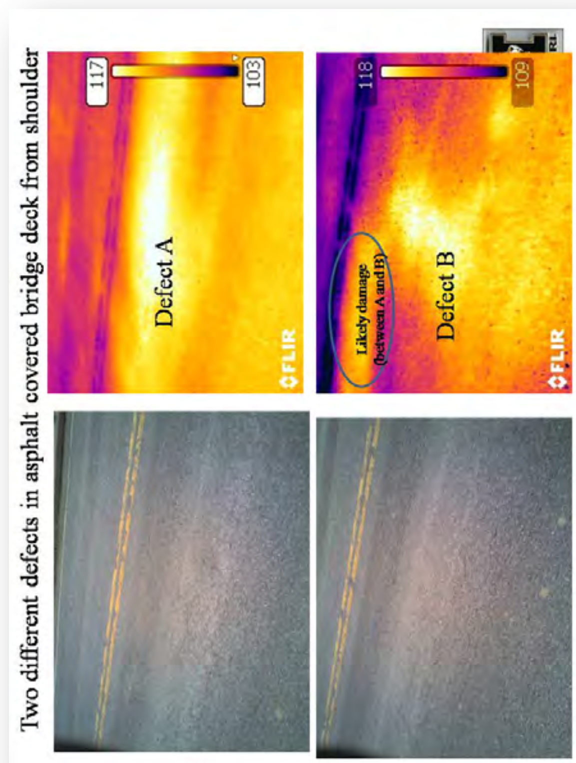

Interior Bay – Delaminated area of bridge soffit
Delam area determined with hammer sounding
Composite of 3 images
Image match points – Diaphragm (top), splice (middle) and diaphragm
MISSOURI


Delam area determined with hammer sounding
Morning
Late afternoon
Interior Bay – Delaminated area of bridge soffit
MISSOURI


Spot
115 °F
FLIR
119
113


Defect A and B in asphalt covered bridge deck from shoulder, opposite side of road
115
104
Defect A
Defect B
FLIR


Spot
45.7 °C
FLIR
48.5
35.1


Two different defects in asphalt covered bridge deck from shoulder
117
103
Defect A
118
109
Likely damage (between A and B)
Defect B
FLIR

Defect under live traffic Field data (top), scale adjusted in office (bottom)

Review

- Capturing a good image requires
  - Correct Level and Span
  - Setting Image Parameters
    - Focus
    - Range
    - Composition
- Thermal Tuning
- Lens selection

Thermography
Module 5, Using the camera

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OREGON.gov
Oregon Department of Transportation
pennsylvania
Wisconsin Department of Transportation
Texas Department of Transportation
Minnesota Department of Transportation
MDOT Department of Transportation
New York State Department of Transportation
MoDOT Missouri Department of Transportation

Using camera and software

- Using the camera is relatively easy
- Using the software is not difficult but requires some consideration of certain protocols

The FLIR T620 with 45 degree lens and professional software

3

The FLIR T620

4

The FLIR T620

5

The Basics of the T620

- **Zooming:** To manually zoom, move the zoom button left/right. For Auto Focus push and release the center of the focus button.
- **Focusing the Camera:** To manually focus, turn the focus ring on the infrared lens left/right. For Auto Focus push and release the save button
- **Auto-Adjusting the image:** To automatically adjust the level and span of the image, push the A/M button and select Auto. Default setting for the camera is auto adjust.
- **Manual-Adjusting the image:** To adjust it manually push the A/M button and select Manual. Push the joystick left/right to adjust the span and up/down to adjust the level.
- **Switching between infrared and digital views:** press the camera button to switch between the two camera views, infrared and digital.
- **Saving an Image:** To save an image press and hold the save button until the picture is taken.
- **Opening an Image:** Push the archive button to open the most recently saved image. Images will appear as thumbnails, use the joystick to scroll through the images. To view a selected image, push the joystick down and the image will appear larger on the screen.
- **Closing a menu:** To close a menu press the Menu/Back button. Note: While a menu is open you will not be able to take any pictures.
- **Choosing Palette:** To change the color palette and the object temperature range, push the Menu button and use the joystick to select Palette. In the palette tab, select the desired palette.
- **Video:** To take a video, press the Menu button and use the joystick to scroll down to Mode. Select Mode by pressing down on the joystick. Under the mode tab select Video using the joystick.

The Basics of the T620

- **Changing Temperature Scale Level:** The camera should display a live infrared image which can achieved by selecting the Camera mode using mode button and joystick. The camera should be in Manual adjustment mode. To change the temperature scale level press the **A/M** button and select manual, then move the joystick up/down.
- **Changing Temperature Scale Span:** The camera should display a live infrared image which can achieved by selecting the Camera mode using mode button and joystick. The camera should be in Manual adjustment mode. To change the temperature scale span press the **A/M** button and select manual, then move the joystick left/right.
- **Zooming in/out:** To zoom in or out on a picture press the zoom button left/right to adjust the zoom.
- **Taking Different Measurements:** To take different measurements press the measure button and scroll through the different options using the joystick.
- **Adding/Removing information to a picture:** To add/remove information on a picture, press the programmable button.
- **Recommended values:** If you are unsure about the values, the following are recommended:

Atmospheric Temperature	+20° C
Emissivity	0.95
Object distance	1 m (3.3ft.)
Reflected apparent temperature	+20° C
Relative Humidity	50%

MIZZOU.

Performing Basic Functions on the T620

- **Taking pictures**
  - Turn on the camera by pressing the on/off button and remove the lens cap.
  - Press the camera button and select what type of photo is preferred by using the joystick.
  - Use the LCD screen to find a desired target.
  - Press and release the save button to auto-focus the picture. **Note:** when doing this hold the camera as still as possible.
  - Press and hold the save button to save the image on the LCD screen.
- **Downloading pictures to a PC**
  - Plug in the USB cord into the computer and bottom of the camera. **Note:** make sure the camera is turned on.
  - Click ok and follow the directions on the computer to save the pictures in an appropriate folder.
  - After downloading the pictures use the safely remove hardware function on your computer before unplugging the camera to avoid problems. **Note:** this is usually found in the bottom right hand corner of the PC screen.
- **Reviewing Pictures**
  - Once a picture or pictures has been saved, press the Archive button.
  - Use the joystick to scroll through the picture saved on the camera
  - Push down on the joystick to get a larger view of each picture. Press the back button to return to the previous view.
- **Add temperature spots/Areas**
  - Press the Menu button.
  - Use the joystick to scroll up to the tools tab.
  - Press the joystick to select the type of measurement desired.
- **Change °F/° C**
  - Press the Menu button.
  - Use the joystick to scroll over to the Mode tab.
  - Use the joystick to scroll down to Settings.
  - Use the joystick to scroll over to the Regional tab.
  - Use the joystick to scroll down to Temperature unit and press down on the joystick.
  - Use the joystick to select the desired temperature unit.

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Image management

- Using Quick Report software
- Using Professional Reporter software
- Uploading .jpg images to MU's online database at thermo.missouri.edu

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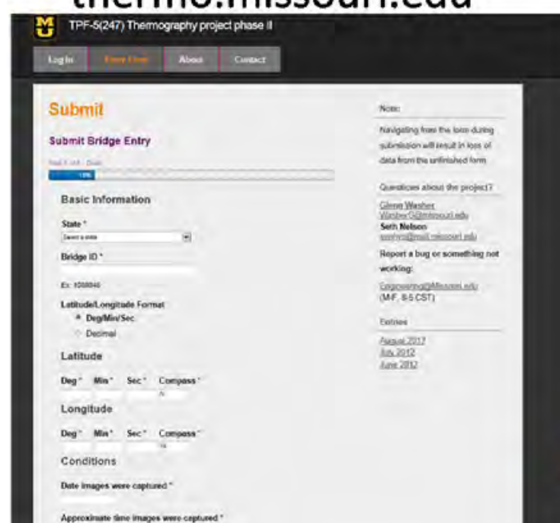
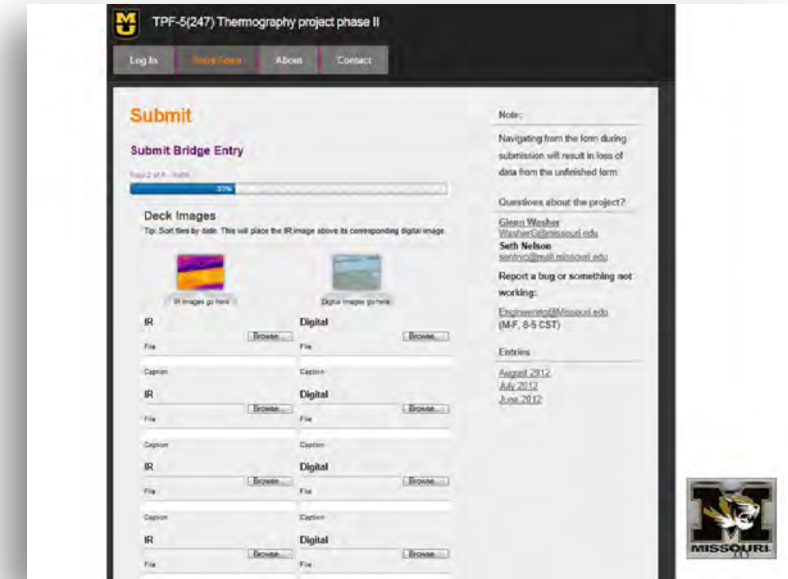
thermo.missouri.edu



MISSOURI



Verification

- Field verification of IR findings
  - hammer sounding, coring, impact echo
- Identify bridge(s)
  - 1-2 bridges in your state with possible defects
    - Ready for demolition?