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Quality Control And In-Service Inspection Technology for Hybrid-Composite Girder Bridges

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16. Abstract

This report describes efforts to develop quality control tools and in-service inspection technologies for the fabrication and construction of Hybrid Composite Beams (HCBs). HCBs are a new bridge technology currently being evaluated by the Missouri Department of Transportation (MoDOT). The report includes analysis of the anticipated damage modes for the HCB members and suitable nondestructive evaluation (NDE) technologies that could be utilized for condition assessment. Infrared thermography (IR) was found to be the most applicable NDE technology for use in quality control/quality assurance (QC/QA) testing to ensure uniform placement of the concrete within the arch, which is critical to ensuring the quality of construction, durability, and capacity of the HCBs. Since this arch is enclosed within an FRP shell, internal voids or honeycombs that may occur during concrete placement are unavailable for visual inspection. It was found that the thermal signature of this arch, which results from the heat of hydration produced during the curing of the concrete, could be imaged on the surface of the composite shell. A procedure for utilizing IR technology to ensure the quality of the concrete placement in the arch was developed, tested and verified through field testing of each of the three HCB bridges constructed over the course of the project. This technology is also suitable for the detection of delamination in the composite shell. Recommendations developed from the research include: implementing thermal imaging technology as a QC/QA tool, utilizing visual inspection for the assessment of the composite shell in-service, and pursuing the application of Magnetic Flux Leakage (MFL) to assess corrosion damage in the strands. MFL technology is currently experimental in nature, and not readily available as a commercial tool. Development of this tool should be tracked in anticipation of future implementation.

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ABSTRACT

This report describes efforts to develop quality control tools and in-service inspection technologies for the fabrication and construction of Hybrid Composite Beams (HCBs). HCBs are a new bridge technology currently being evaluated by the Missouri Department of Transportation (MoDOT). The report includes analysis of the anticipated damage modes for the HCB members and suitable nondestructive evaluation (NDE) technologies that could be utilized for condition assessment. Infrared thermography (IR) was found to be the most applicable NDE technology for use in quality control/quality assurance (QC/QA) testing to ensure uniform placement of the concrete within the arch, which is critical to ensuring the quality of construction, durability, and capacity of the HCBs. Since this arch is enclosed within an FRP shell, internal voids or honeycombs that may occur during concrete placement are unavailable for visual inspection. It was found that the thermal signature of this arch, which results from the heat of hydration produced during the curing of the concrete, could be imaged on the surface of the composite shell. A procedure for utilizing IR technology to ensure the quality of the concrete placement in the arch was developed, tested and verified through field testing of each of the three HCB bridges constructed over the course of the project. This technology is also suitable for the detection of delamination in the composite shell. Recommendations developed from the research include: implementing thermal imaging technology as a QC/QA tool, utilizing visual inspection for the assessment of the composite shell in-service, and pursuing the application of Magnetic Flux Leakage (MFL) to assess corrosion damage in the strands. MFL technology is currently experimental in nature, and not readily available as a commercial tool. Development of this tool should be tracked in anticipation of future implementation.

INTRODUCTION

This report provides an evaluation and analysis of potential inspection challenges and suitable nondestructive evaluation (NDE) techniques to assess the experimental Hybrid Composite Beam (HCB). NDE methodologies assessed include ultrasonic testing(UT), acoustic emission(AE), thermography(IR), magnetic flux leakage (MFL) and tap testing. The overall goal of this research was to implement bridge innovations for reducing cost of bridge construction and maintenance. The experimental HCBs constructed as part of this project are aimed at achieving these goals. HCB technology is new to the state of Missouri and has very limited service experience elsewhere. Therefore, an evaluation of potential challenges and technologies for inspecting these bridges was needed. The objectives of this research were as follows:

- Develop methods for quality control / quality assurance testing
- Evaluate potential serviceability and maintenance challenges

To achieve these objectives, an analysis of the potential damage modes that could affect these bridges was conducted. Potential damage modes include flaws or defects that may occur during the fabrication of the HCB members, as well as in-service damage modes that may occur during the service life of the bridge. Damage modes were identified and are described herein. A survey of available inspection technologies was also conducted to identify tools that could be used to assist in quality control (QC) and quality assurance (QA) testing. The NDE tools identified were focused on QC/QA testing of the concrete arch, which may be placed in a fabrication yard or in the field at the bridge site. Tools suitable for in-service inspection of HCBs are also discussed.

QC/QA testing of the arch using thermography was conducted for each of the members constructed during the project for three HCB bridges. The procedure used for casting the arch was also observed, and a description of the casting process is included herein to document the process used for these experimental beams. These data are documented in anticipation of additional applications of the technology in the future and to record the process utilized in this initial application of the technology.

During the course of the research, thousands of images of the HCB members were captured using infrared cameras. A small subset of these images are included to explain the technology and describe the most significant results found in the research. Tap testing of the composite shell was also completed for one of the three HCB bridges constructed.

POTENTIAL DAMAGE MODES FOR HCB

To properly assess the suitable inspection technologies that could be applied for HCB, it was first necessary to consider the potential damage modes and deterioration mechanisms that could affect these members. The assessment of this information is focused on two time periods: during the fabrication of members, at which time NDE could have a role as a QC/QA tool, and through the service life of the bridge, when NDE could play a role in maintaining the safety and serviceability of a bridge. The damage modes considered were focused on those that are most likely to occur during the fabrication and service life of the bridge.

Figure 1 shows a schematic diagram of a HCB member to illustrate the anticipated damage modes. These include cracking of the composite shell surrounding the core, delamination in the composite shell, voids in the concrete, and corrosion damage in the prestressing strands that form the tie of the internal arch in the HCB members. Each of these damage modes is discussed in this section.

Voids In Concrete

Concrete is poured into the arch of the HCBs and acts as the compression chord for the member. Self-consolidating concrete (SCC) is used for casting this arch member. SCC typically has a higher flowability and workability than regular concrete. These characteristics improve SCC’s ability to flow through forms and reinforcement and consolidate with limited or no vibration. The arch forms an important compression member for the HCB, and as such, voids or other discontinuities in the arch concrete may lead to reduced load capacity, increased deflections and long-term serviceability issues. As a result, it is important that this material be continuous and without significant voids resulting from improper placement of concrete.

Such voids, if they existed, are expected to be present following the concrete pour, and as such can be assessed during the construction phase and repaired if necessary. The internal concrete arch is contained within the FRP shell of the member, and polyiso foam is used to fill the HCB member and form the shape for the internal arch into which SCC in placed. Given the geometry of the section, voids are hidden from view by the composite shell and foam inserts, and as such these voids are not detectable through visual inspection at the time of construction.

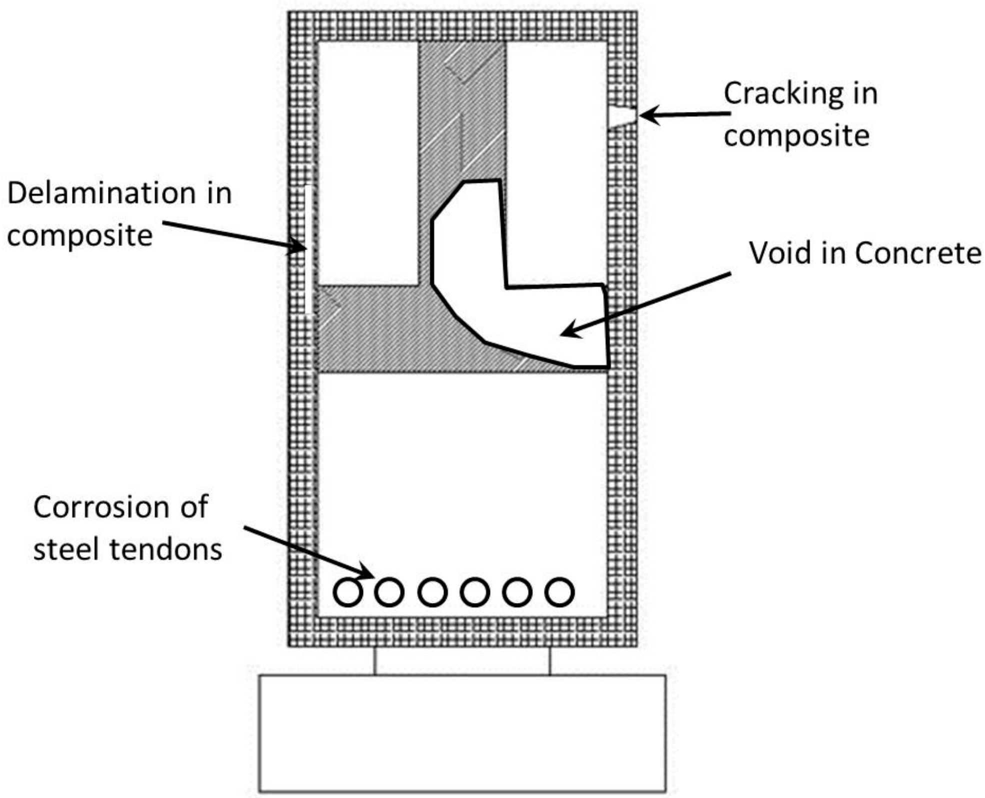

Figure 1: Example of potential damage modes for HCB.

Damage Modes for Shell Laminate

There are two primary potential damage modes for the composite shell of the HCB - cracking of the shell and delamination between the layers of the shell. The potential damage mode of cracking, or breaking of the fibers, may result from loading or overloading of the beam, the effects of fatigue loading, buckling of the compressive flange, or local flange or web buckling due to overloading [1, 2]. Generally, such a damage mode would progress to become surface-breaking and therefore can be observed through normal visual inspection.

The effect of ultraviolet radiation on the shell of the hybrid composite beam can increase the likelihood of cracking during the service life of the structure. Usually this cracking initiates as visual cosmetic damage in the surface resin of the shell which does not affect the structural properties of the FRP shell. This cosmetic damage includes surface color changes, loss of pigment, and loss of the surface luster of the laminate. Even though these damages are only visual cosmetic degradations in the surface resin, they can induce more significant damage in the shell [3, 4]. These degradations can eventually decrease the ultimate strain in the resin as well as decrease the specific toughness of the resin's surface layer. These decreases in the surface resin properties can cause the modulus of elasticity of the surface to increase and lead to crack propagation in the HCB shell.

Ultraviolet radiation damage to the shell of the HCB can be prevented through different additives in the resin formulas, or an application of a gel coat to the surface of the beam's shell. This gel coat is a thick resin layer on the exterior surface of the laminate which can be applied through spraying or rolling after the manufacturing of the beam. The gel coat also improves fire protection of the beam and provides an additional barrier against moisture[3]. Ultraviolet radiation damage is most likely to affect the fascia members of a bridge structure, particularly those facing the southern sky where solar exposure is anticipated. Generally, ultraviolet radiation damage to the composite can be observed visually, and affects the outermost layers of the fibers. Given that the composite shell only has a moderate role in the primary load paths in the structure, such damage is unlikely to be a significant safety concern over the service life of a HCB structure.

Delamination between the layers of the composite shell is also a potential damage mode. Delamination is likely to occur due to improper application of resin during the fabrication of the composite shell. Voids in the resin material or resin-starved areas may develop delamination[5]. Delamination has occurred in the lab testing of the

HCBs; however, this has only occurred during load testing that exceeds the factored demands[3]. The results of these tests are usually debonding of the web laminate from the interior polyiso foam core. Because this has occurred only when loading exceeds factored demands, and such a condition is unlikely for an in-service bridge, delamination of the composite shell has not been observed in the field.

Delamination can be detected using tap-testing methods or using infrared thermography (IR), as described later in the report. Since this damage mode is typically present at the time of fabrication, it can be appropriately addressed during QC testing. Localized delamination of the shell has only a modest effect on the load-carrying capacity of the composite material because shear transfer can be provided through the surrounding, well-bonded composite materials. As a result, delamination in the composite surrounding the HCB core is primarily a workmanship issue that can be addressed through the QC process.

Secondary potential damage modes were stated in the HCB Design and Maintenance Manual and are listed below with a short description of each [3]:

- Blistering: Identified as bumps in the surface, usually caused by a porous surface resulting from a poor gel coat application.
- Presence of Moisture: The laminates applied to the HCB shell are subject to moisture absorption. This can lead to degradation of the composite material
- Abrasion or Tearing: This type of damage may occur due to high water that results in debris impacting the composite or vehicles impacts below the bridge, which could result in section loss.
- Creep, Flow, or Rupture: These damage modes are of little concern due to the stiffness of the concrete and steel reinforcement, which creates low stresses and loads on the FRP laminates.

These secondary damage modes to the composite shell are generally available for assessment through visual inspection.

Steel Corrosion

Corrosion of the steel prestressing strands that form the tie in the HCB may be a longer-term maintenance concern. Because these strands are enclosed within the beam section, and hence unavailable for visual inspection, this damage mode will not be observable during normal, routine inspections. The steel strands are galvanized to provide a sacrificial material that will act as the anode in electrochemical corrosion process. This will provide adequate corrosion protection in the near term. However, collection of moisture in the bottom of the HCB section where the steel is located could create a corrosive environment for the steel that corrodes the sacrificial zinc and leads to section loss. The box-like geometry of the HCB members is more likely to retain moisture than, for example, a member with an open section geometry. The box section may retain water in a manner similar to a voided slab bridge, where water collects in the voids despite weep hole that may be provided to prevent this from occurring. In the HCB members, pathways for water to enter to box section through the deck and concrete arch should be anticipated, based on past experience with voided slabs and adjacent box girder bridges.

Pitting corrosion in the steel strands is of particular concern. Localized areas of section loss, or pits, can develop such that the overall section loss may be nominal, but deep, localized pits reduce the tensile strength of the strand and result in strand fracture. Such localized corrosion damage may result from damage to the galvanizing during fabrication, from holidays in the galvanizing, or from localized degradation that penetrates the zinc layer.

An additional concern for galvanized strands stems from the fact that the tie chord is formed from high-strength prestressing strand. Such high-strength steel is susceptible to hydrogen-assisted cracking; high levels of hydrogen may be produced in the corrosion process for the zinc coating the strand, leading to hydrogen embrittlement of the prestressing strand, cracking or fracture of the wires, and subsequent reduction in load-carrying capacity.

Presently, there are no viable, commercially available and practical technologies for identifying strand fracture, with the possible exception of radiographic testing (RT). Field applications of RT are relatively rare for highway bridges due to the perceived health and safety concerns, and the practical constraints of testing in the field. However, magnetic technologies developed for the detection of section loss and strand fracture in prestressed beams offers a technology with potential for this application, and this technology will be discussed later in the report.

NONDESTRUCTIVE EVALUATION TECHNIQUES

This section of the report describes NDE technologies that may have application for QC/QA or in-service inspections of the HCBs. A survey of available NDE technologies was conducted with a focus on the assumed damage modes previously described. Those technologies most likely to provide suitable tools for the assessment of HCBs were down-selected for inclusion in this report. These include ultrasonic testing (UT), infrared thermography (IR), acoustic emission (AE), magnetic flux leakage (MFL) and tap testing.

Ultrasonic Testing

Ultrasonic testing has been in use as a nondestructive testing method for many years. Typically, ultrasonic tests are used to determine the thickness of a material or detect and evaluate the size of flaws and defects, such as corrosion, voids, and cracks. This NDE method utilizes sound wave propagation to conduct these measurements. During this project, ultrasonic pulse velocity measurements were considered as an NDE technology with the potential to be applied to the concrete arch for the detection of voids, honeycombs or poor quality concrete.

UT uses high frequency sound energy to propagate waves, normally ranging from 50 kHz to 50 MHz in frequency, through a material to conduct the testing. A UT system is typically comprised of two primary elements - a pulser/receiver and one or more transducers. The pulser produces a high voltage electrical pulse which acts on the transducer to create a pulse of acoustic energy, i.e an acoustic wave. The ultrasonic energy then propagates through the material, interacting with the composition of the material. If there is a defect in the material, or if the wave reaches the opposite side of the material, the wave is then reflected back to the receiver. The reflected wave portion is then transformed into an electrical signal to be displayed on the system’s screen for data analysis.

Generally, smaller defects require shorter wavelengths to be detected, and as such higher frequencies are typically used, around 2-4 MHz. Larger defects typically require lower frequency, and longer wavelengths, around .5 to 2 MHz, to be detected. Due to these frequency requirements, higher frequencies (shorter wavelengths) are used to test finer grained materials, such as metals, while lower frequencies (longer wavelengths) are used to test coarse grained materials, such as concrete. Increasing wavelength also increases the penetrating power of the wave, such that lower frequency waves can propagate over larger distances than high frequency waves. The rule of thumb for flaw detection using UT is that the wavelength cannot be larger than twice the size of the defect. Generally, frequencies of approximately 50 KHz are used for testing concrete, 2.25 MHz or greater is typically used for metals.

The primary limitation for UT is that a coupling medium is needed to transmit ultrasonic energy from the transducer into the material. As a result, direct access to the surface is required, and the surface must be adequately prepared such that coupling can be achieved. Additionally, because the ultrasonic energy is reflected at boundaries of the materials, layered materials present a particular challenge. The reflection coefficient, i.e. amount of energy reflected at a the boundary of the materials, can be determined from the relative acoustic impedances of the material involved; when acoustic impedance differences are high, the reflection coefficient is also high. As a result, very little ultrasonic energy is transmitted across the boundary.

A conceptual diagram of the setup for ultrasonic pulse velocity for a hybrid composite beam is shown in Figure 2. As shown in the diagram, the internal foam lies between the composite materials on the surface of the member and the concrete arch within the member. As a result, ultrasonic waves cannot be transmitted directly into the arch. Therefore this approach was considered ineffective for assessing the quality of the concrete arch.

UT can also be used to assess delamination in the composite material, through the use of surface waves propagating in the composite layer. Such technology has been previously demonstrated for use in aerospace vehicles and pressure vessels. However, such an approach is costly, time consuming and requires hands-on access to the entire surface of the composite material to be assess. Infrared thermography, described later in this report, is capable of detecting these delaminations without the requisite surface access necessary to implement ultrasonic technology. Consequently, UT for detecting delamination in the composite material was not pursued during the course of the research.

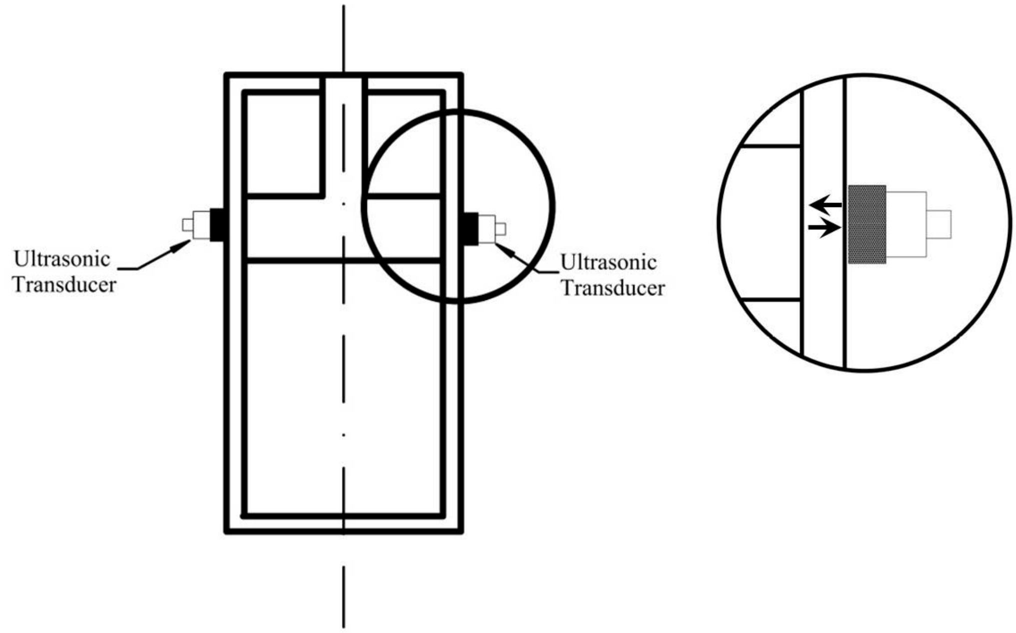

Figure 2: Testing Setup for Ultrasonic Pulse Velocity for HCB.

Acoustic Emission

Acoustic Emission (AE) is a method of detecting the onset of damage in materials based on burst of elastic energy associated with the formation of the damage. The technique was first developed in the 1950’s by materials scientists exploring the formation of the microstructures in metals, and later developed as a means of monitoring the development and propagation of the damage due to static and fatigue loading [6]. Since that time, AE testing has become common for testing pressure vessels, aerospace vehicles and other engineering applications. More recently, AE methods have been developed exploring the application of AE as an NDE method for concrete and concrete structures and composite materials.

The fundamental theory behind the generation of acoustic emissions in materials is that propagation (growth) of a crack releases a small burst of elastic energy caused by the extension of the crack surface on an atomic level, and plastic-zone development processes surrounding the crack tip. This burst of elastic energy propagates as an acoustic pulse through the material and can be detected by sensors coupled to the surface of the material under test. For composite materials, cracking of the resin matrix and fracture of individual fibers produce acoustic emissions that can be monitored as a means of evaluating damage induced during loading cycles.

The acoustic emissions are typically discriminated from other noise that may be present, such as traffic noise on a bridge, rubbing of bearings, etc., based on waveform characteristics[7]. Analysis of monitoring results typically consists of assessing the number of AE events per unit time, with increased AE activity being associated with crack nucleation and growth.

AE has traditionally been implemented for bridges as a monitoring technology, with a number of sensors placed permanently on a structure to monitor an area for incipient crack growth [8-10]. Typical applications include monitoring the AE activity of known cracks or assessing the effectiveness of a retrofit for arresting crack growth, as opposed to monitoring a bridge with no known cracks [11, 12]. Applications of AE for bridges comprised of composite materials has been very limited, although this technology is often used for composite-overwrapped pressure vessels during load testing[13]. Monitoring systems for AE testing typically consists of multichannel (16 channels+) systems that can be mounted in the field and communicate data through phone lines or via cell phone connections.

The primary advantage of AE testing is the ability to monitor a large volume continuously, and to discriminate “active” damage, e.g. crack growth under load. Location of a defect can be assessed using multiple sensors on the material through cluster analysis and triangulation calculations.

One of the main disadvantages of AE is directly related to its main advantage. AE typically detects defects or damage that is actively growing. Existing defects or damage that are inactive (i.e. not growing) typically cannot be detected, because they do not produce acoustic emissions. An exception to this is concrete with distributed cracking, for which acoustic emissions stemming from rubbing of the crack faces may be used to qualitatively assess the health of a concrete member[14].

AE is a feasible technology for long-term monitoring of the <u>composite shell</u> for HCBs. Monitoring of the concrete arch and steel strands using AE is infeasible, due to the foam core positioned between these elements and the accessible surfaces of the member. AE signals generated from damage in the concrete arch or steel stands would be attenuated before reaching the surface, where sensors would typically be placed.

The composite shell plays only a modest role in the structural capacity of the HCB, and this composite shell is available for visual inspection to assess damage that may develop. Consequently, it was concluded that AE was not a beneficial technology to be pursued for the in-service condition assessment of the HCBs.

Infrared Thermography

Infrared (IR) thermography has been used for a number of years for the condition assessment of concrete decks[15]. This technology is based on the principle that heat conduction through a material is affected by the presence of defects or discontinuities in the material, and that this disruption of heat flow manifests in observable temperature variations at the surface of the material[16-18]. These variations in surface temperature can be observed and recorded with IR cameras, which image the IR energy emitted from the surface.

IR cameras detect the electromagnetic radiation emitted from a body, which is proportional to the fourth power of the temperature of the body. All materials emit radiation in the infrared range when their temperature is above absolute zero (-273 ºC). IR cameras are used to infer temperature of a material by measuring the electromagnetic radiation emitted or reflected from the surface [19]. The power of emitted radiation can be expressed by the Stefan-Boltzmann equation:

$$E = \varepsilon\sigma T^4 \tag{1}$$

Where E is the radiant energy emitted by a surface at all wavelengths, ε is the emissivity of the materials, σ is the Stefan-Boltzmann constant (5.67×10^{-8} $W/(m^2K^4)$) and T is the temperature in degrees Kelvin. The emissivity of an object is a relative measurement of rate at which the object emits radiation, 1 being a perfect emitter and 0 being no emission at all. In general, materials that are most common among civil structures, such as concrete, wood and asphalt pavement all have relatively high emissivity, between 0.9 and 1.0. The composite wrap surrounding the HCB core is expected to have a similar emissivity. The emissivity is a surface property, such that changes in the surface of the material as a result of debris, staining, oil, and water can influence the apparent temperature of the surface [17, 20].

For concrete structures, IR has traditionally been used for the detection of subsurface corrosion damage that results in delamination in the concrete. When a subsurface delamination exists in the concrete, it disrupts heat flow through the concrete. During the warming of the day, the area above the delamination warms more quickly than the intact concrete surrounding the delamination, resulting in increased IR energy being emitted from that area. During a cooling phase overnight, the concrete surface above a subsurface delamination will likewise cool at a faster rate than the surrounding concrete and appear as a cooler area in an infrared image [21].

However, for the HCB beams evaluated through this research, a different approach to thermal testing was evaluated. Following the placement of the concrete in the arch section of the member, the heat of hydration developed in the arch provides a significant heat source. If this heat source is sufficient, the thermal signature of the concrete arch could be apparent on the surface of the HCB. As shown schematically in Figure 3, this would result in increased emission of IR energy in the area of the arch, resulting in the observable signature on the surface that can be imaged using a thermal camera. This requires that the thermal energy be sufficient to penetrate approximately one inch of foam surrounding the arch, as well as the composite overwrap. If a void was present in the arch, the thermal energy from hydration would not be available in the area of the void. As a result, the thermal signature of the arch would not be apparent in thermal image of the surface. The approach of utilizing the heat of hydration for imaging subsurface features such as the arch has not been previously attempted, to the knowledge of the research team. However, if effective, this could provide a critical tool for QC testing of HCBs at the time of fabrication. This approach was evaluated through the course of the research and determined to be successful. Results will be described in the following sections.

If thermal images were not collected at the time of the fabrication of the member, the integrity of the concrete arch could also be evaluated in-service, provided that the thermal inertia of the concrete in the arch was sufficient. For such a scenario, the concrete arch would be thermally out of phase with the foam and composite that surrounds it. This would result in the arch appearing cold during the early parts of the day, when environmental temperatures are increasing, and hot during the early evening, when environmental temperatures were cooling. Again, there is no prior experience with such an approach, but this approach was evaluated through the research and found to be successful.

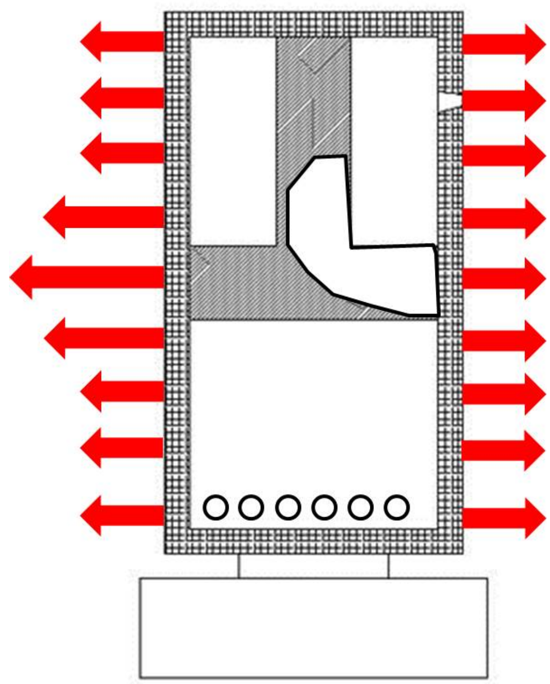

Figure 3: Schematic diagram of IR emission from a HCB during hydration of concrete.

One of the main advantages of IR testing is the ease of the testing procedure. The equipment is hand-held, and since it is a non-contact method, the testing can be performed at a distance. Access to the surface to be assessed is not required, and thermal images can be captured from distances of 100 ft or more. Therefore, testing can be done quickly and without disrupting traffic, construction, or any other process on site. For this project, thermal testing was the only technique used that could adequately detect the concrete through the FRP shell and polyiso foam core.

IR Cameras

Two different IR cameras were used to collect images during the course of the research. A FLIR S65 research-grade camera with a temperature sensitivity of 0.08 °C and an image size of 320 x 240 pixels was used to collect some IR images of the HCB members during the early stages of the project. A FLIR T620 with a temperature sensitivity of 0.04 °C and an image size of 640 x 480 pixels was also used. The selection of the IR camera was based simply on the availability of the camera; either device has adequate capabilities to conduct the inspections.

Tap Testing

A simple method for searching for delamination and debonded areas is by mechanical sounding. Mechanical sounding is a method by which a metal or plastic object is used to strike the surface of the composite material. The tone produced by the impact is then analyzed; delaminated areas are identified by their distinctive hollow tone. This method can also be used to find delamination in concrete and debonding between concrete repair materials and the original concrete.

Sounding has been implemented for aerospace structures utilizing a metal coin (e.g. a quarter), and is commonly referred to as a coin-tap test. The low mass of a coin results in a high-pitched tone that can reveal delamination between layers of composite and possibly between the composite and the bonded substrate. For deeper features, a larger mass should be used so that the depth of the material is excited by the tapping. For composite retrofits on civil structures, a rock hammer or other suitable impact device may be used, though care should be taken to avoid damaging the composite material. The use of hammers allows for detection of features further from the surface, but near-surface features such as delamination between layers of composites may be obscured. A ¼ in. to ½ in. steel rod, approximately 6 inches in length, can also be used effectively in civil retrofit applications. The advantage of using this type of device is that it is readily available, since it can be formed from a piece of rebar. It can also provide both a high-mass and low-mass impactor depending on the orientation of the rod when impact is made.

Tap testing was utilized in this project to test the composite shell for one of the HCB members. However, IR technology is also well suited to this application and, since thermal images of all of the surface areas of all of the members was planned, tap testing was not utilized otherwise. Additionally, tap testing requires hands-on access to the entire area to be tested. As noted above, thermal imaging does not require this level of access, and is therefore more efficient and practical than tap testing.

Magnetic Flux Leakage

Magnetic flux leakage (MFL) is an NDE technology with the potential for detecting fractured prestressing strands embedded in concrete, and it has been a topic of research for several years[22, 23]. This technology may have application for condition assessment of the strands that form the tie of the HCB members

The MFL method works by inducing a magnetic field within the prestressing steel strand and detecting the leakage of that field that results from sudden discontinuities in the strand (i.e. fractured strand or section loss)[24]. The process of damage detection in the strand is analogous to the process involved in magnetic particle testing (MT). For MT, finely divided iron particles are attracted to magnetic fields leaking from a crack in the surface of the steel. For MFL, the leaking magnetic fields are detected using coils, Hall effect or SQUID (superconducting quantum interference device) sensors [25, 26]. The leaking field can be detected through significant air gaps or concrete cover; detection through concrete cover of up to 11 inches have been reported in the literature [23, 27]. For the case of an HCB, the composite overwrap and the polyiso foam are diamagnetic materials that will behave similarly to air or concrete cover. As such, an MFL technology developed for detection of damaged strand in prestressed girders could also be applied to the HCB.

The method, as applied for a prestressed beam, is shown schematically in Figure 4. Rare earth magnets are typically used to provide opposing magnetic poles. These poles are separated by a certain distance such that the magnetic field between the poles penetrates the concrete to induce magnetization in the embedded steel strand.

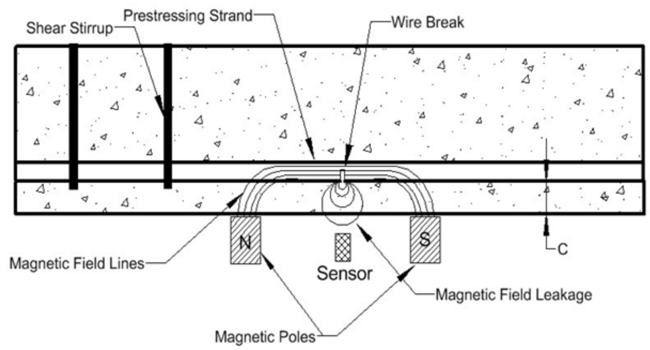

Figure 4. Magnetic Flux Leakage test schematic.

A sensor is used to measure the ambient magnetic field level at its position between the magnetic poles. The sensors and magnets form a sensor head that is scanned across the surface of the concrete axially aligned with the embedded steel strand. Sudden changes in the geometry of the embedded steel, such as a broken wire, result in a sudden change in the ambient magnetic field as the sensor head is scanned along the surface [28]. Changes in the cross-sectional area of the steel within the aperture of the sensor head also results in variations in the ambient magnetic field levels. These changes are less localized in nature relative to the response created by a fractured strand. Mild steel, such as steel stirrups, also results in variations of the ambient magnetic field and this complicates the interpretation of results [28]. Varying concrete cover can also create variations in the measured ambient field. However, even with these recognized limitations, the MFL approach provides a potential solution to nondestructively detecting broken and corroding strands embedded in concrete, and may also provide a technology for assessing the prestressing strands that form the tie of the HCB

An example of the current state of the technology is shown in Figure 5. This figure shows a MFL unit developed at the University of Wisconsin [23]. Figure 5A shows a plan view of an MFL unit; Figure 5B shows the orientation of an MFL unit in use on the soffit of a box girder bridge. As shown in Figure 5A, the sensor head unit is comprised of two magnet modules, a sensor module, and an encoder that tracks the position of the unit as it is scanned along the length of the member. Magnetic field levels are monitored as the unit changes position along the member as shown in Figure 5B.

Research in the U.S. has typically focused on measuring the leakage field resulting from direct induction, i.e. during magnetization. An alternative approach is to utilize remnant or residual magnetization resulting from magnetizing the embedded steel. Electromagnetics are used to magnetize the embedded steel from distance up to ~12 inches [27]. The resulting magnetization of the embedded steel, which remains (at a reduced level) after the electromagnet is removed, creates a dipole in the area of a fracture of the strand or wire [24, 27]. Some research has suggested this method is more effective than induced magnetic fields; however, comparison data is limited.

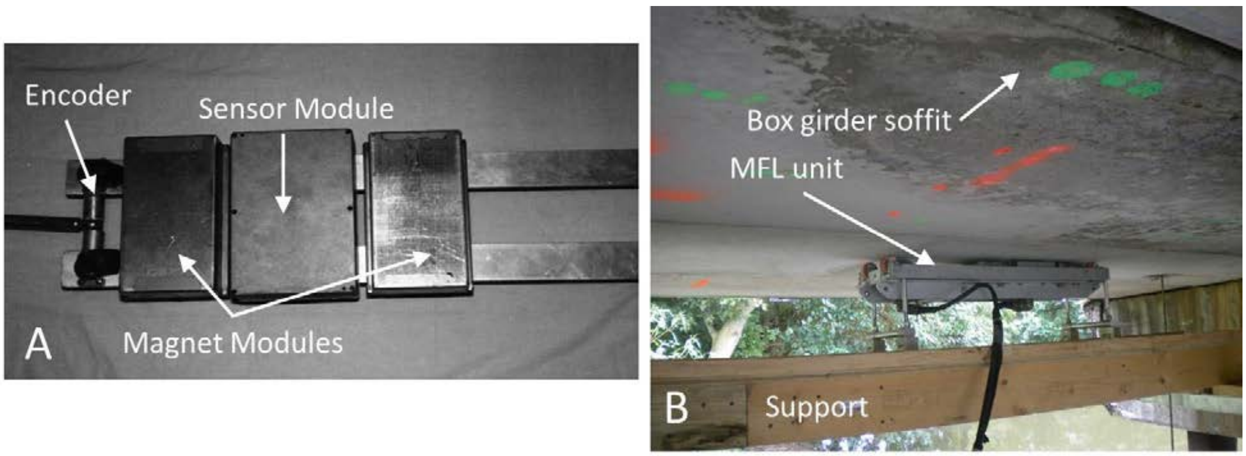

Figure 5. MFL system components (A) and system deployed on a prestressed box girder (B).

Currently, MFL technology is not sufficiently developed to have been evaluated during the course of this research. The technology is experimental in nature, with the only systems available being research prototypes developed at the University of Wisconsin. However, in the longer term, such a technology may provide an important tool for detecting damage in the steel strands that form the tie of the HCB.

FIELD OBSERVATIONS

This section of the report will describe the field observation of the procedures used for placement of concrete for each of the three HCB bridges constructed during the course of the project. During the course of the project, researchers attended each of the three casting procedures for the concrete arch to observe the procedure used to cast the arch, and to evaluate the application of IR as a QC/QA tool. The research team also revisited bridges in-service, to evaluate that application of the thermal testing to the in-service beams. The results of these tests will be presented in later sections of the report. Tap testing of FRP shells for one of the bridges was competed to evaluate this technology. However, there were no defects identified during the tap testing. Since the method is comprised of striking the surface and listening to the tone produced, there are no results to present.

Bridge B0439 Arch Pour

The pour for the first set of hybrid composite beams for bridge B0439 took place over a one week period in August 2011. The pour site was in Mountain Grove, MO, located about one mile from the concrete plant. The procedure covered multiple steps. First, since HCBs are a fairly new procedure and technology for bridge construction in Missouri, a mock pour was scheduled the week before to practice the pour procedure. A wooden box served as the HCB shell, with one wall consisting of see-through Plexiglas in order to see if the procedure would allow the concrete to fill the entire arch. The mockup, shown in Figure 6, was one half of the length of the actual HCB, since the concept was to have concrete pushing itself down from the middle of the arch until the end block and entire arch were both filled completely. The same foam that was used in the HCBs was used in the mock up as well. The procedure proved to be successful in the mockup with the arch and end block completely filled. Some of the self consolidating concrete (SCC) did seep through the foam, but the arch remained intact without any voids visible through the Plexiglas wall.

Figure 6. Photographs of HCB mock-up.

During the B0439 pour, only one concrete truck was used to deliver the SCC to the pour site; therefore it took an average of 45 minutes from the end of one beam pour to the beginning of the next. Once the concrete mix for the SCC was deemed acceptable on site, the SCC was then poured into the HCBs' arches. The beams were placed together in pairs at the pour site, with enough space left in between the pairs to park a truck. The SCC was poured into the beams directly from the concrete truck, as shown in Figure 7. A funnel was used to aid in the pour from the truck into the HCBs' concrete arch. During much of the pouring process, workers were observed discarding chunks of concrete that had begun to solidify in the truck.

The procedure for placing the concrete was as follows: the concrete would first be poured into one end hole until the end block was filled. The workers would then switch to the other end to fill in the opposite end block. The same procedure was used for the quarter holes, filling one then switching to the other, until finally concrete was poured into the center pour hole. This procedure would allow the concrete to keep pushing itself down until the arch was completely filled. This would become apparent on site due to concrete pushing up through the pour holes as well as through the shear connectors. To aid in the consolidation and flow of concrete through the arch, workers on site tried to use vibration on the concrete. To do this, workers would 'vibrate' the shear connectors sticking out of the top of the HCB, since these went down into the concrete arch. Workers would either hit the connectors with a hammer or shake them back and forth with their hands.

Figure 7. Photgraph showing concrete rising through shear connectors and workers vibrating connectors to consolidate SCC.

Bridge B0410 Arch Pour

The pour for the second set of HCBs for bridge B0410 took place over a two week period in May 2012. Bridge B0410 consisted of three double web HCBs that span 120 ft. The pour site was at a precast plant in Chesapeake, Virginia operated by Concrete Precast Systems.

The pour procedure for these double web HCBs generally followed the same process as that of B0439. However, there were some minor differences. For bridge B0410, the concrete was poured into the arches using a pump truck that was placed adjacent to the member. Different consolidating techniques were also used for the SCC in this bridge. A concrete vibrator was used to aid in concrete consolidation instead of vibrating the shear connectors. The vibrators were placed into the pour holes, along the top crevice where the shear connectors come out of the beam, and through some shear connector openings. These procedures can be seen in Figure 8 shown below.

Figure 8. Photograph showing vibrator and concrete placement for bridge B0410 HCB.

Because B0410 consisted of double-web members, concrete could not be filled in one arch, or web, without counterbalancing it in the other. The pour was initiated at one end block, and once filled, the workers would move to the opposite end block on the other web and fill that end block. This simple procedure was to prevent the HCB from tipping over due to the weight of the concrete. The remaining end blocks were then filled. From there, the workers followed the same procedure, going from one quarter hole to the opposite web and opposite end quarter hole. When finished with the four quarter holes, the workers finished the pour with the two middle pour holes.

The pour for the bridge B0410 took two weeks to complete, due to weather conditions that included rain for a portion of the first week. One double web HCB was poured during the first week, while the remaining two were poured the second week.

During the pour of the first double web beam, it became apparent to workers and on-site quality control (QC) personnel that something had gone wrong with the concrete pour into the arch. Workers realized that the concrete was not rising as it should to the top of the arches inside the two webs. QC personnel then ran a simple test by sticking a ruler down through the shear connectors and pour holes to see if there were any voids in the concrete. A void map was then constructed from the information gathered and is shown in Figure 9. Voids were present in both arches and both ends of the beam. Additional concrete was poured into the arches through the shear connectors and additional pour holes drilled into the beam to fill the voids approximately one week after the original casting process. The voids were determined to be due to decreased flowability in the concrete at the time of the pour.

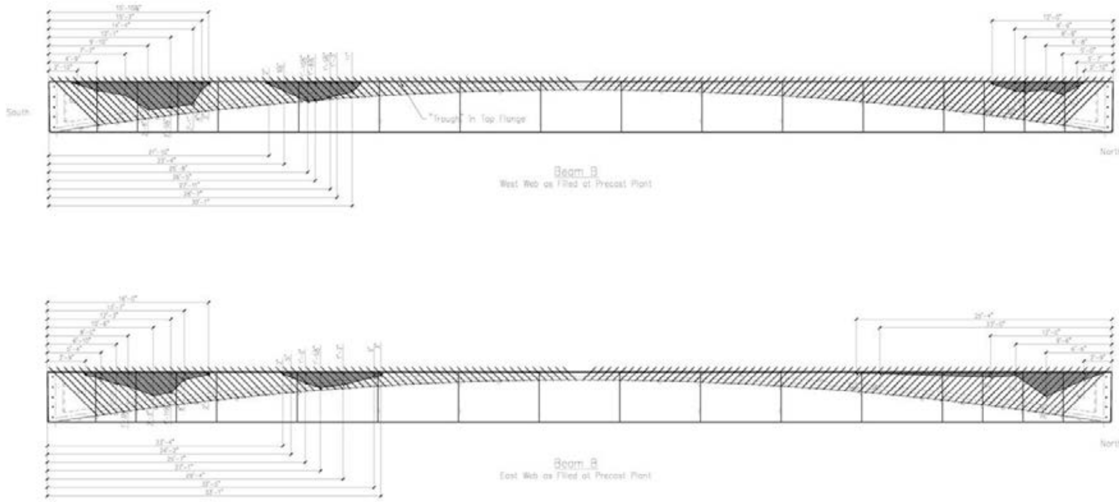

Figure 9. Diagrams of voids in SCC arch of B0410.

Bridge B0478 Arch Pour

The pour for the set of HCBs for bridge B0478 took place over two days in August 2012. The pour site was the location of the bridge in Black, Reynolds County, MO. The HCBs were delivered to the bridge site and placed on the abutments before the pour. This was the only of the three bridges that had the concrete arch placed with the HCBs placed in their final positions on the piers and abutments. Therefore, a pump truck was required to pour the concrete into the arches since the bridge was already erected, as shown in Figure 10. However, since the HCBs were single web beams, the pour procedure more closely followed that of the first bridge, B0439. Multiple concrete trucks were used to transport the SCC out to the bridge site in order to keep the concrete pumping continuously.

Figure 10. A & B: Photographs of concrete pump truck (left) and spans 1 &2 during concrete placement (right) for Bridge B0478

It should be noted that when pouring began on the first day, it was a goal that all 12 beams were to be poured in the same day. However, delays were experienced as a result of difficulty with the quality of the SCC; as a result, the pouring procedure was extended into the second day.

RESULTS

This report will discuss the application of thermography as a QC/QA tool and as an in-service monitoring device. This technology has application for assessing voids in the concrete arch and delamination of the composite overwrap. During the course of the project, no delamination of the composite material was observed; consequently, this report focuses on the application of thermography for the assessment of voids in the concrete arch.

Camera Procedure And Placement

Throughout this project, thousands of thermal images of the three bridges were captured. To achieve the best results in the thermal images, certain procedures need to be followed. For example, the camera needs to be properly focused and appropriately oriented relative to the member being assessed. The best results are obtained with the camera oriented normal to the surface of the beam. During the course of the research, this orientation was not always possible to do operational constraints that prevented appropriate access.

When access was limited to prevent a normal-angle image to be captured, the camera would be placed adjacent to the beam facing down the length of the member. This placement resulted in an isometric picture of the HCB, or, in other words, a picture of the length of the member at a low angle. Thermal images captured at such low angles typically exhibit a thermal gradient in the image that results from the variation in distance from the camera to the surface being imaged. This gradient results from the attenuation of the IR energy as it propagates through the air.

An example of an image captured at a low angle, along with a diagram of the camera's placement, can be seen in Figures 11 A & B. It can be observed in Figure 11A that the surface of the member closest to the camera generally appears warmer than surfaces located far from the camera. This thermal gradient can compromise the quality of the thermal image and/or make interpretation difficult. The location adjacent to the beam was used on Bridges B0410 and B0478 because of the placement of the beams. For Bridge B0410, the pictures were taken at the pour site. The HCBs were placed very close together in order to make it easier on the pump truck during the pouring. Due to this location, the isometric pictures needed to be taken as there was no space available to place the camera at a normal angle with the surface of the member. For Bridge B0478, since the beams were placed on the abutments before the concrete was poured, access to position the camera at a normal angle was not possible.

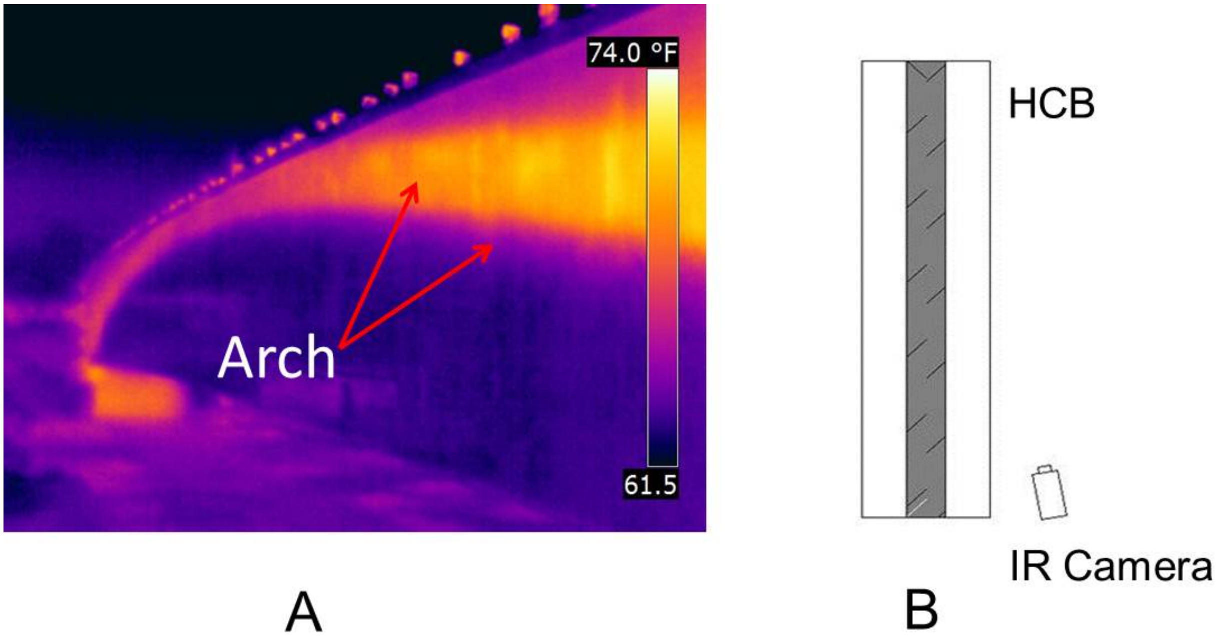

Figure 11. IR image of HCB length (left) and diagram of corresponding camera location (right).

The preferred camera location was directly perpendicular, or normal, to the surface of the beam. The camera was typically located about 10 to 15 feet away from the beam at a normal angle with the surface of the member. This placement produced an image of the full height of the beam, and without the thermal gradient typical of an image captured at a low angle. An example of an image captured from the normal position, along with a diagram of the camera's placement, can be seen below in Figures 12 A & B. This type of camera location was used whenever possible for all three bridges.

The camera placement is an important consideration looking forward toward implementing the IR technology as QC tool. To provide the best images, allocation of adequate spacing for the camera to be position normal to the surface is required. When the concrete arch is placed in a fabrication yard, this space can be provided by properly positioning equipment and positioning the beams at an adequate spacing, typically 15 to 20 ft. apart. When casting of the arch occurs in-place at the bridge site, positioning the camera to be most effective is more problematic, although images can still be captured effectively, as shown in Figure 11.

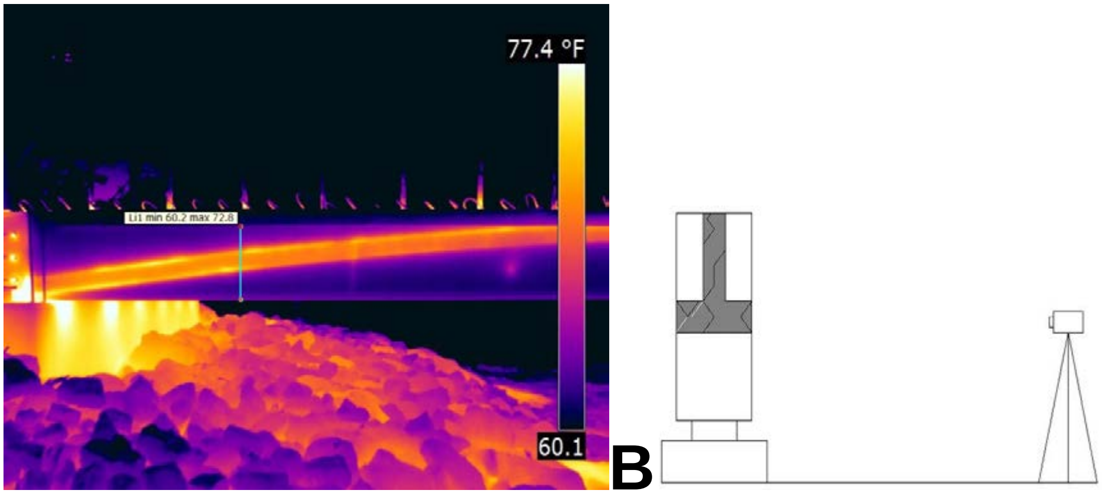

Figure 12. Thermal image at normal angle to HCB (right) with diagram of corresponding camera location (right).

Mock-up Testing

The mock-up of the HCB was tested using the S65 thermal camera as a proof of concept test to establish if the proposed methodology for assessing the integrity of the concrete arch was implementable. The forms for the mockup specimen consisted of plexiglass and plywood, as discussed previously. It was found during the testing that the thermal signature of the arch could not be imaged well through the Plexiglas wall of the form. These materials are often opaque in the IR range, so this result was not unexpected. Thermal images of the plywood wall of the form clearly showed the thermal signature of the concrete following placement. Figure 13 illustrates a thermal image of the concrete arch, along with a photograph of the mockup. Note that the photograph of the mockup is taken from the side with a plexiglass wall, and shows the void prior to concrete placement. The thermal image is taken from the opposite side of the specimen, and as such has the opposite orientation.

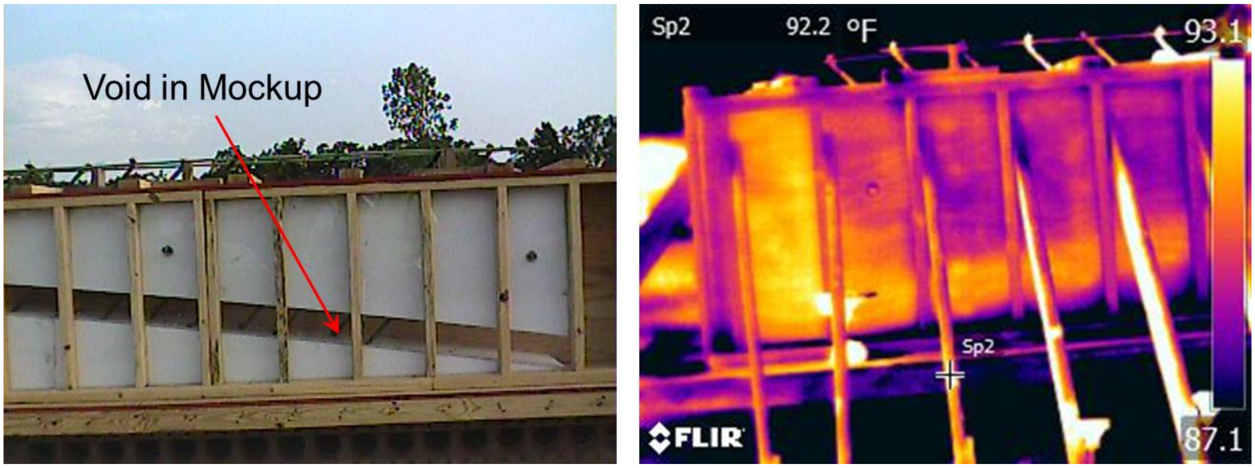

Figure 13. Photograph (left) and thermal image (right) of the mockup specimen showing concrete arch.

This initial test indicated that the concept of imaging the thermal signature of the concrete arch during the hydration of the concrete was a feasible approach. The general form of the concrete arch is apparent as a thermal contrast in the image, represented by different colors. This “thermal signature” of the concrete arch results from the heat of hydration of the concrete, as previously mentioned.

Quality Control Testing of the HCB

The application of the infrared thermography for QC testing of the HCB was demonstrated through the project. The procedure for acquiring IR data was to utilize a hand-held infrared camera to acquire data from a standing position adjacent to the HCB. A typical IR image is shown in Figure 14. This figure, which was acquired 24 hours after the concrete pour, illustrates how the process works. As shown in the image, the heat of hydration of the concrete in the arch results in a thermal signature on the surface of the composite that images the internal arch. This thermal signature is revealed through the foam inserts and the composite wrapping that surrounds the arch.

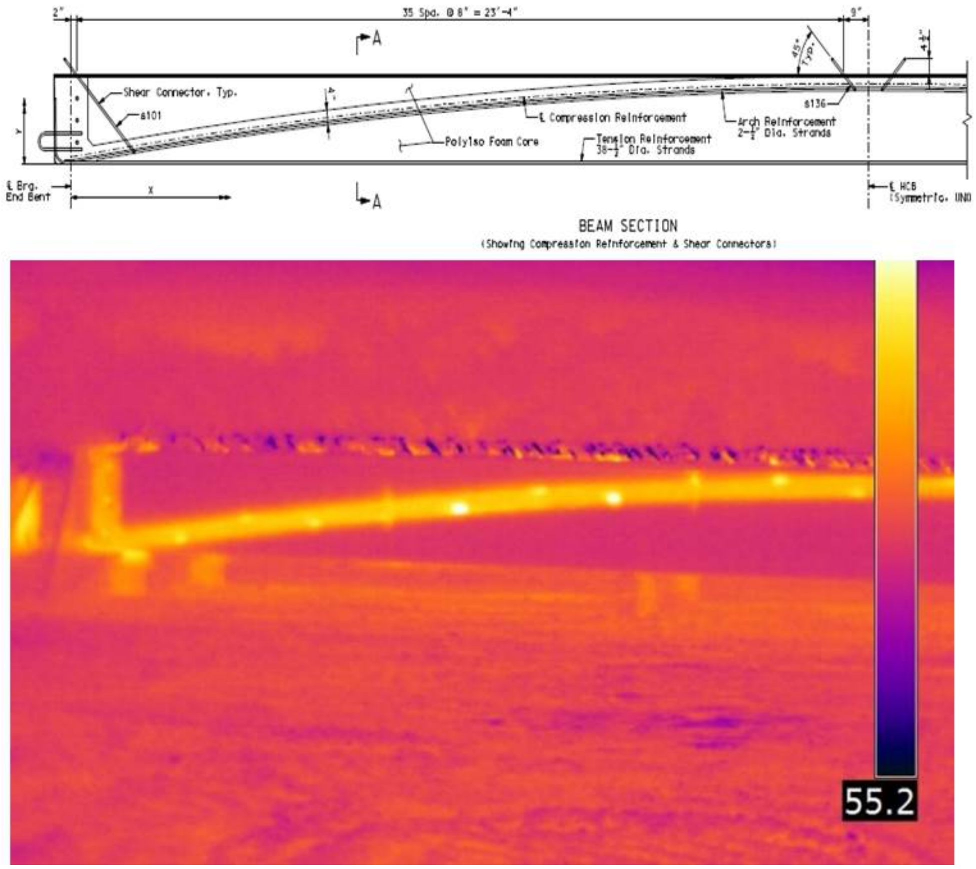

Figure 14. Example thermal image showing thermal signature of the arch during the hydration of concrete.

Testing was completed during the fabrication of each of the three HCB bridges; testing was completed at the fabrication yard for two of the bridges, and for the third bridge testing was completed during the erection process as shown in Figure 15. In this figure, a span cast the previous day is imaged using the IR camera. Workers on the bridge shown in the photograph (Figure 15, right) are placing concrete on the next span.

Environmental conditions such as ambient temperature changes are typically a critical factor for imaging subsurface damage in concrete, such as corrosion-induced delamination. For QC testing of HCBs, where the heat of hydration of the concrete is creating the thermal signature of the arch on the surface of the composite, environmental conditions are much less critical. Because the arch is generating its own heat source it can be imaged regardless of the temperature conditions. Caution should be used in the case of rain, simply because the presence of water on the surface will obscure the thermal image.

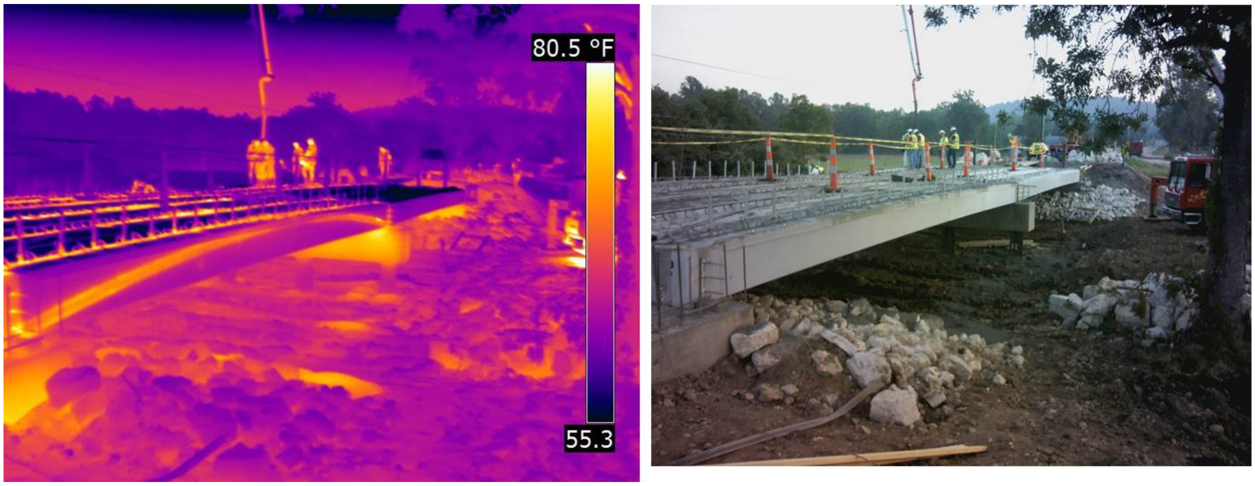

Figure 15. Example of IR image (left) and photograph of HCB (right) being placed in the field.

Timing of QC Imaging

A study was conducted to determine the optimum time for capturing images to assess the concrete arch following concrete placement. Thermal imaging will be most effective when the thermal contrast between the concrete arch signature and the surface of the beam is greatest. Thermal images were captured at various times ranging from 4 to 48 hours after concrete placement to assess this effect. The temperature contrast was determine from the equation:

$$T_{contrast} = T_A - T_B$$

Where:

$T_A =$ Apparent temperature on the surface of the HCB above the concrete arch and

$T_B =$ Apparent temperature on the surface of the HCB

Figure 16 shows a typical location selected for calculating the temperature contrast on the surface of the beam. This contrast was used determined to optimum times for inspection. The thermal contrast can also be used to quantify the temperature contrast developed from the hydration of the concrete or to quantify the contrast resulting from ambient temperature variation once the hydration of the concrete is complete.

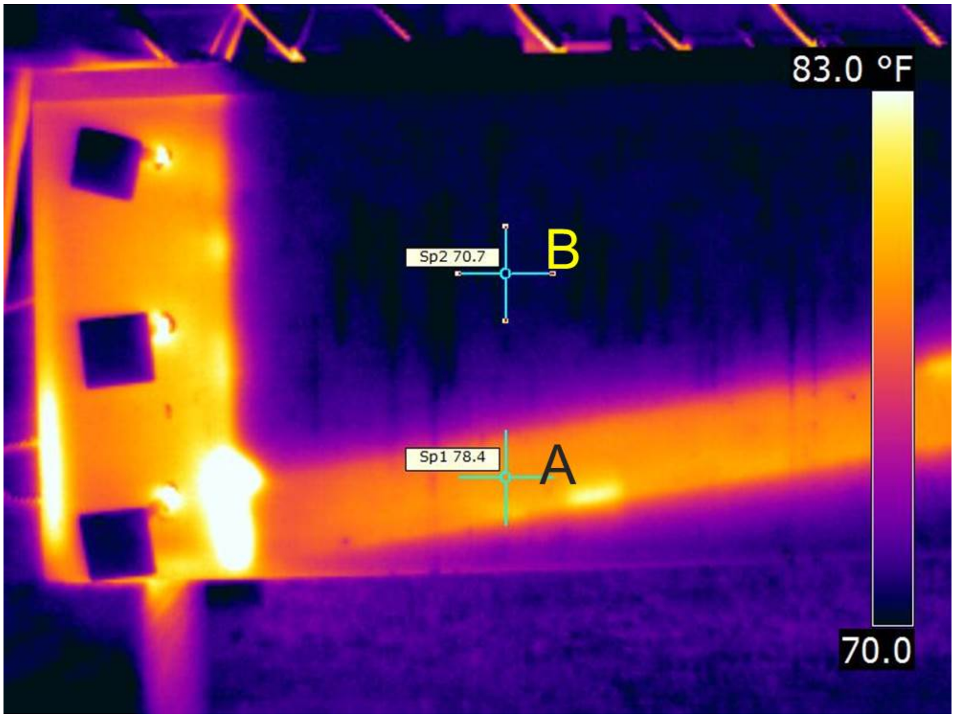

Figure 16. Thermal image illustrating how temperature contrast was determined.

Figure 17 shows the temperature contrast for the arch over a 48 hour time period. This figure represents the general behavior of all of the HCB's studied during the research, and shows that the optimum time for conducting an inspection for QC purposes is approximately 24 hours after the concrete in poured. The thermal contrast between the composite shell surface above the arch and other surface areas was almost 9 °F at this point in time. The thermal contrast was reduced at later measurement times. Images captured as late as 48 hrs after placement of the concrete still provided adequate thermal contrast to enable imaging of the concrete arch. From these data, the time period over which QC testing of the arch using IR should be conducted is approximately 6 hours to 48 hours after the placement of concrete, with the optimum time being ~24 hours after placement.

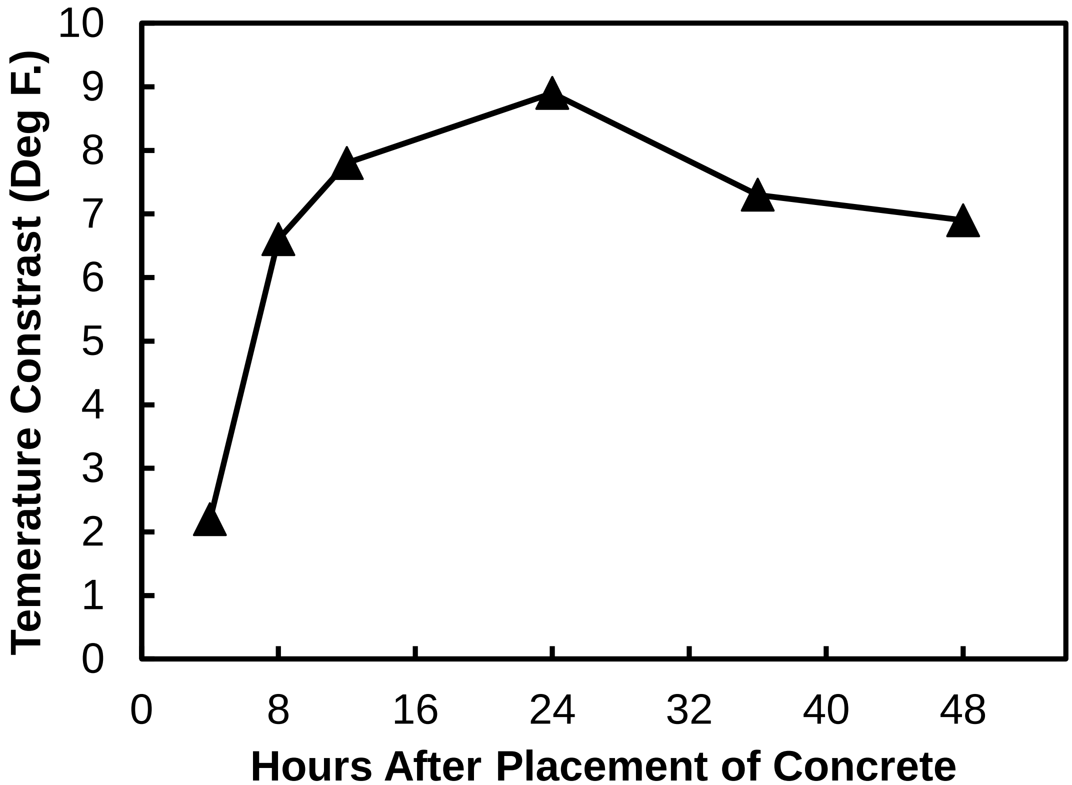

Figure 17. Thermal contrast at surface caused by hydration of concrete during 48 hours after placement.

Detection of Voids

Thermal images were captured for each of the HCB bridges, typically 24 hrs and 48 hrs after the concrete placement. Generally, these images reveal an intact arch producing a strong thermal signature on the surface of the HCB. However, during the casting of Beam 1 of bridge B0410, the placement of the concrete resulted in several voids in the concrete arches for each web of the member. These voids were apparently caused by a lack of workability of the concrete, possibly due to the concrete beginning its set prior to placement. The presence of the voids in the concrete arch was recognized by the on-site QC personnel, because the concrete was not rising in the forms in certain locations along the length of the girder. These voids were detected in the thermal images captured 24 hours after the pour. Figure 18 illustrates the detection of the voids in the thermal images, in a composite image formed by combining separate, individual thermal images of portions of the beam. The blurriness of the images that can be observed in Figure 18 was attributed to high humidity at the time the images were captured. High humidity conditions can cause the auto-focus function of the camera to not perform well. Regardless, the figure clearly shows the voids in the arch of the beam. Shown in the figure is the West web (A) and the East web (B) of the double – web HCB for bridge B0410. The void maps developed by on-site QC personnel is also shown to verify the thermal imaging results.

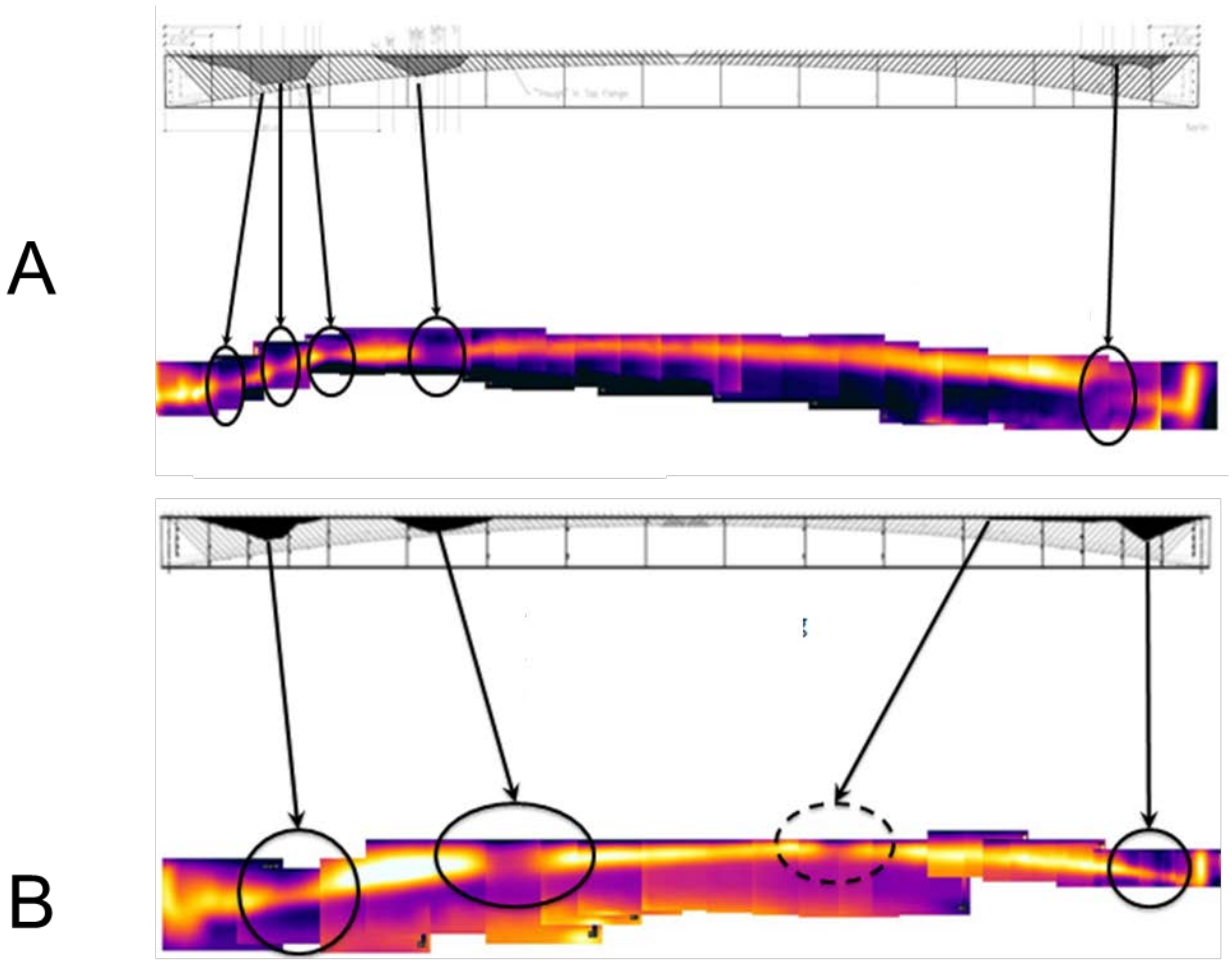

Figure 18. Composite thermal images of the West (A) and East (B) webs of beam 1, HCB B0410.

The voids in the member result in the thermal signature of the arch disappearing at the locations of the voids. At these locations, the heat of hydration of the concrete is not available because the concrete is missing, i.e. there is a void. Figure 19 quantifies the thermal detection of one of the voids detected in this member, from data captured 48 hrs after concrete placement. As shown in the figure, the signature of the concrete arch is not apparent in the thermal images; the temperature variations along a line shown in Figure 19A are shown in Figure 19B. The data presented in Figure 19B quantitatively illustrate the color variation in Figure 19A.

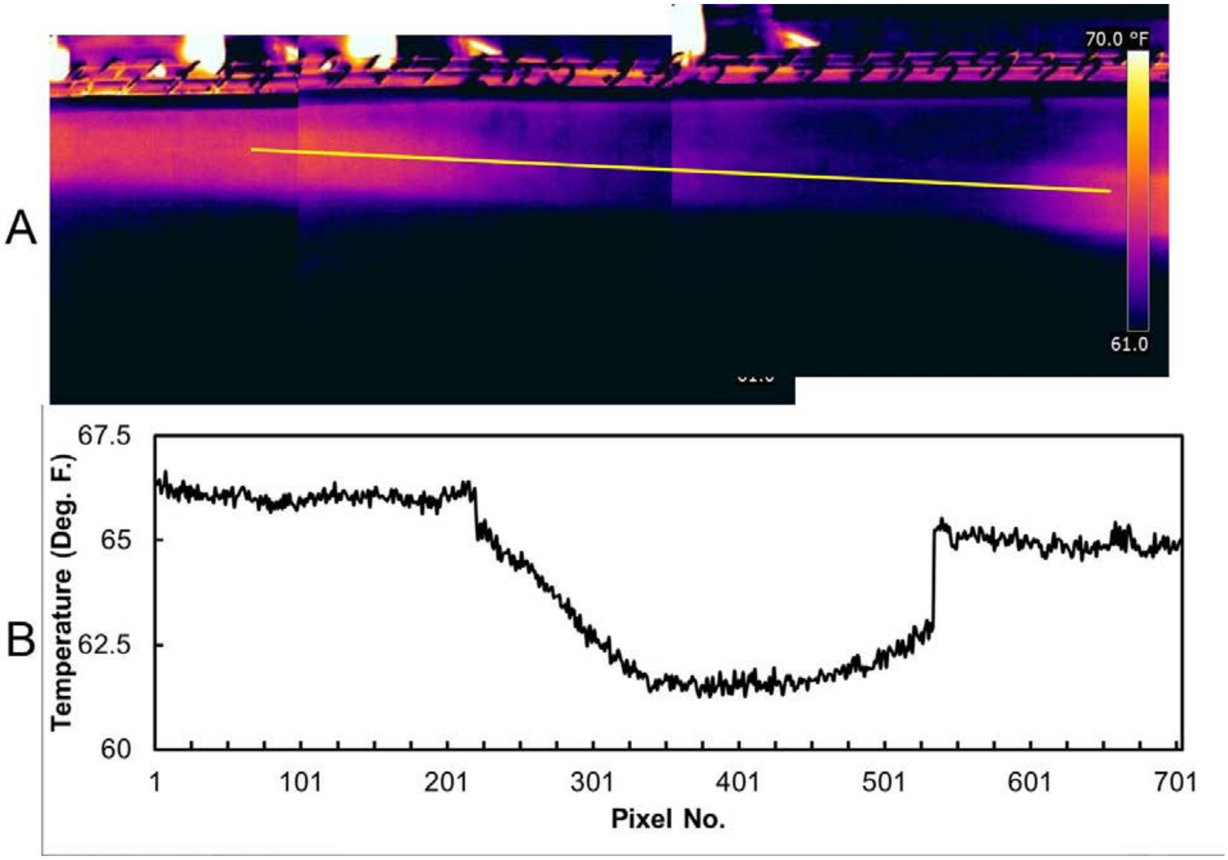

Figure 19. Composite thermal image of void in B0410 (A) and temperature variations (B) along the line shown in (A).

These figures clearly illustrate the ability of the IR thermography to detect the presence of voids in the arch, through the polyiso foam and composite overwrap that surrounds the arch. Given that this area in unavailable for visual inspection, this technology will provide an important tool for QC/QA testing at the time of casting of the arch, either in the field or in the fabrication yard. For the example shown here, the voids could also be detected from the top of the arch, however, voids or honeycombs may also occur without being apparent through the top of the member. The thermal method is an effective way to detect these voids.

Anomalies

During the course of testing, there were a consistent pattern of anomalies appearing in the thermal images. These anomalies were represented by periodic “hot spot” appearing on the images, usually at locations on or near the surface above the arch. Figure 20 illustrates some of the thermal anomalies observed. These "hot spots" may have resulted from the concrete placed in the arch void leaking through the polyiso foam, resulting in a larger thermal contrast reaching the surface of the composite shell in localized areas adjacent to the arch. These "hot spots" have greater thermal contrast than the arch itself, indicating that the heat of hydration is conducting across less material, that is, this is concrete that has pushed through the foam included in the HCB, and hence is closer to the surface. Leakage to the concrete through the foam inserts was observed during the mock-up testing, as noted previously.

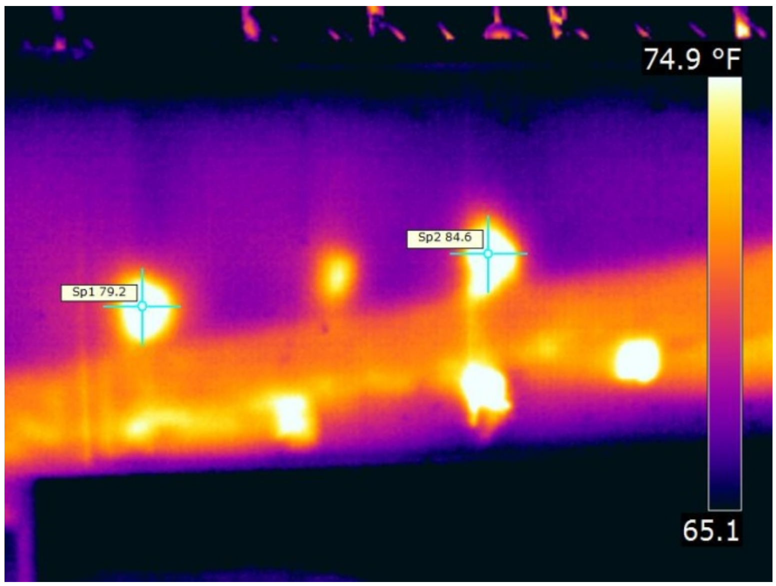

Figure 20. Images showing thermal "hot spots" typically observed following concrete placement.

These anomalies were further assessed during testing 1 and 2 years after placement of the concrete. Figure 21 illustrates the locations of the anomalies one year after concrete placement for bridge B0439. As shown in these figures, the anomalies generally follow the thermal pattern of the concrete arch, that is, they are warmer during periods when the composite shell is cool, and cooler during periods when the composite shell is warm. This is likely due to the thermal inertia of the arch, which is out of phase with the variations in the surface temperature of the composite shell. As a result, these anomalies appear as "hot spots" during the nighttime, and "cold spots" during the warming cycle of the day. Thermal inertia or thermal mass, ***I,*** is a measure of the ability of the material to conduct and store heat. It is computed as the square root of the product of thermal conductivity (***k***), density (***ρ***), and heat capacity ($\boldsymbol{C_p}$) as

$$\boldsymbol{I = \sqrt{k\rho C_p}}$$

Heat capacity (i.e. specific heat) is defined as the amount of heat needed to raise the temperature of a unit mass of a material by one degree. This property describes the ability of material to store heat. The volumetric heat of a material can be calculated as the product of the density and the specific heat of the material. It is a measure of the quantity of heat required to produce a unit temperature change in a unit volume [29]. For the HCB, the significant thermal inertia of the concrete arch results in the temperature of the arch being out of phase with the surface temperature of the HCB in areas other than above the arch. These data indicate that these anomalies are part of the arch, i.e. this is concrete that has leaked through the foam to be in contact with the composite shell.

It is also possible that some of these thermal anomalies result from steel connection or fasteners that are in contact with the composite shell and embedded in the concrete, such that they follow the thermal pattern of the arch and conduct heat toward the surface of the composite shell. Regardless, these anomalies are not believed to be detrimental to the performance of the HCB.

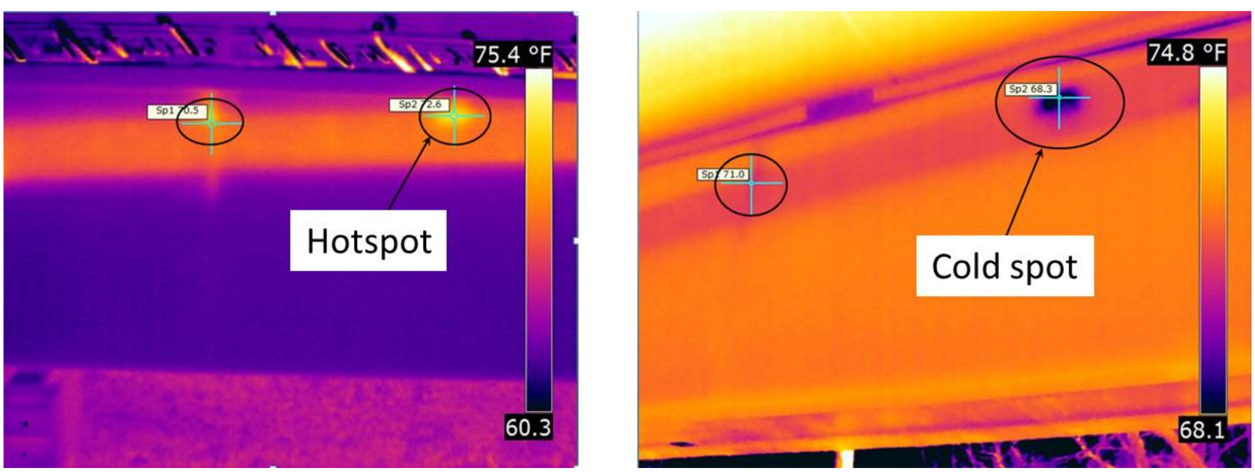

Figure 21. Example of anomalies observed in the area of the arch one year during the night (left) and during the day (right).

In-Service Testing

Thermal images of the HCBs were captured after the bridges were placed in-service, to assess if IR thermography could effectively image the arch after the hydration of the concrete was complete. The arch of Bridge B0439 was placed in August 2011. Thermal images were captured at the time of the casting, as well as in March 2012 (seven months after casting) and in April 2013. The results of these tests indicated that the concrete arch could be imaged after the hydration of the concrete was complete, due to the thermal inertial differences between the concrete arch and the surrounding foam and composite materials. Figure 22 illustrates the behavior of the concrete arch during the morning and evening hours. Figure 22 A shows a thermal image of the HCB at 6 pm in the evening, at which time the concrete arch appears cooler than the other portions of the HCB shell. The temperature gradient along the line shown in Figure 22A is shown in Figure 22B. The data in Figure 22B illustrate the actual temperature variation between the composite shell and the arch signature. Figure 22C shows an elevation of the HCB at 5 am in the morning. In this image, there is a significant gradient through the depth of the member, as illustrated in the gradient along the line shown in Figure 22D. This gradient results from the significant thermal energy stored in the concrete deck and parapets of the structure. Because these concrete elements store the thermal energy from the previous day, conduction of this thermal energy into the HCB results in the gradient shown. The gradient results in the arch signature being difficult to observe in the image, relative to the image captured at 6 pm.

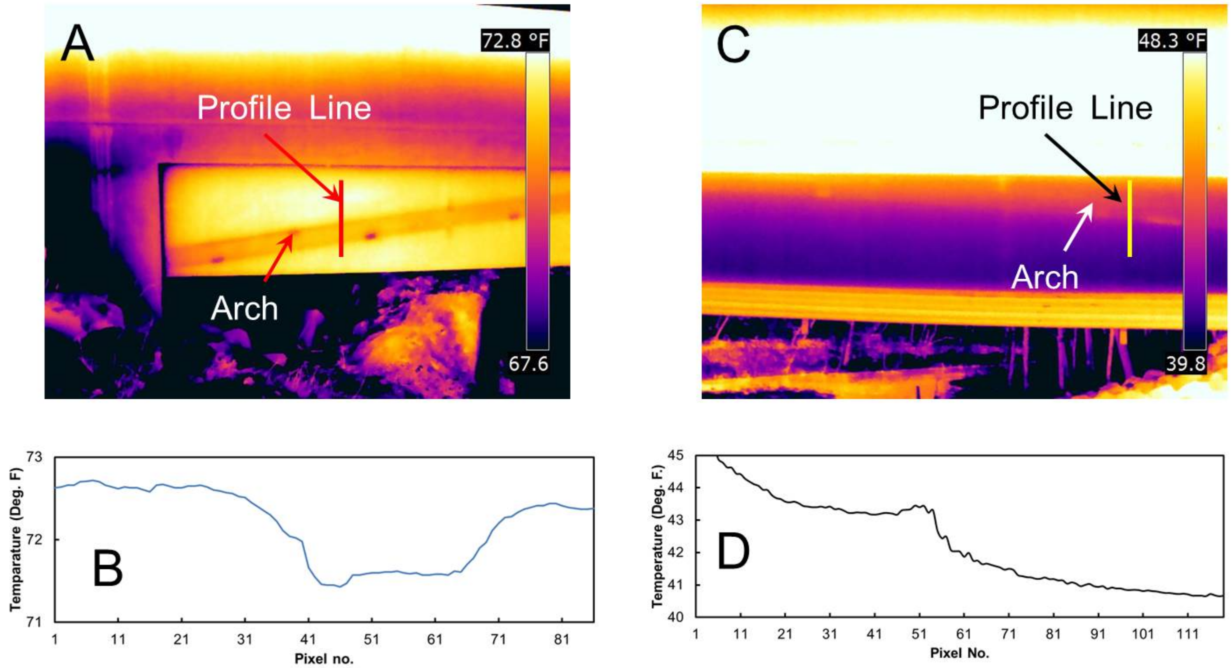

Figure 22. Thermal images of B0439 20 months after concrete placement showing HCB at (A) 6 pm with thermal profile (B), and (C) 5 am with thermal profile (D).

The thermal contrast between the concrete arch signature and the composite shell was monitored over a 24 hour period to determine the optimum times to conduct an inspection for an in-service bridge. As shown in Figure 23, the greatest thermal contrast between the concrete arch and the composite shell occurs in the early morning hours, prior to sunrise. However, as noted above, the thermal images may be more difficult to interpret at this time due to the thermal gradient along the elevation of the member. It should also be noted that the behavior of the concrete arch is opposite of, for example, a delamination in the composite shell would be. A delamination in the concrete shell would be cold in the overnight hours, when that arch signature is warmer than the surrounding area. During the day, a delamination would appear warmer than the surrounding area. As a result, such a defect could be easily discerned from the arch signature. There were no composite delamination defects observed over the course of the project.

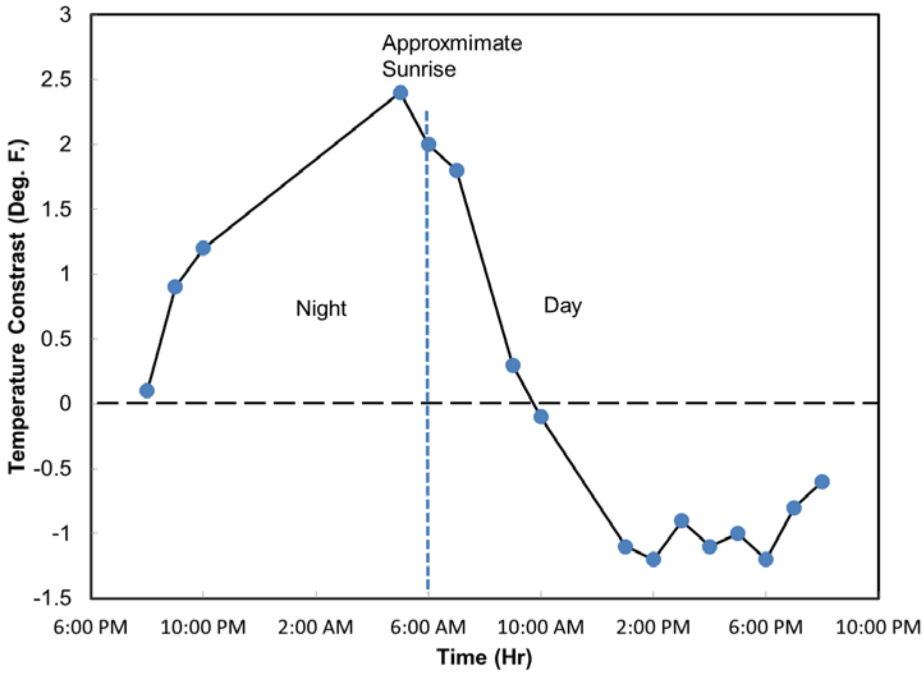

Figure 23. Thermal contrasts over a 24 hour period for B0439, 20 months after placement of concrete arch.

CONCLUSIONS

The objectives of this research were as follows:

- Develop methods for quality control / quality assurance testing
- Evaluate potential serviceability and maintenance challenges.

These objectives were achieved in the research through a review of potential damage modes for the HCB members, an assessment of available inspection technologies, and the development of the appropriate NDE technology for QC testing of the concrete arch that forms a critical element of the HCB.

Damage modes for the HCBs included voids or lack of consolidation in the arch, damage of the HCB composite shell, and corrosion damage of the prestressing strands used as the tension tie in the arch. Voids or lack of consolidation in the arch was assessed using IR thermography. Methods for implementing IR thermography for detecting voids in the concrete arch were developed, tested and verified during the course of the testing. This technology successfully detected voids in the arch section during the casting of the arch for bridge B0410. The approach developed was innovative and capitalized on the heat of hydration generated during the curing of the concrete. The IR thermography approach was demonstrated as an ideal solution for QC/QA of the concrete arch to detect voids in the concrete.

Damage modes identified for the HCB composite shell are generally available for visual inspection. Therefore, NDE technologies for this application were not pursued. However, the thermal methods used for assessing consolidation of the concrete arch are suitable for detection of delamination in the composite material. This technology can be applied as a QC/QA tool to assess the workmanship of the composite construction, or as an in-service inspection tool.

NDE technologies for the condition assessment of the prestressing strands are limited. Corrosion damage of these strands is an important long-term concern for the in-service performance of HCBs. Experimental methods based on MFL were described in the report. This technology is experimental at this time, and generally not available for practical bridge inspections.

Recommendations

Based on the research, the following recommendations are made:

1. Thermal imaging should be implemented as a QC/QA tool during the fabrication of the HCB bridges for the detection of voids in the concrete arch and delamination in the composite.
2. Visual inspection is a suitable tool for assessing the long term behavior of the composite shell
3. Progress on the development of practical tools for conducting MFL should be monitored, and this tool should be considered for monitoring of corrosion damage of the prestressing strand within the HCB members in the future.

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