

1-29-2016

# Bridge-in-a-Backpack™ Task 6: Guidelines for Long Term Inspection and Maintenance, 2016

Maine Transportation Research Division

Maine Department of Transportation

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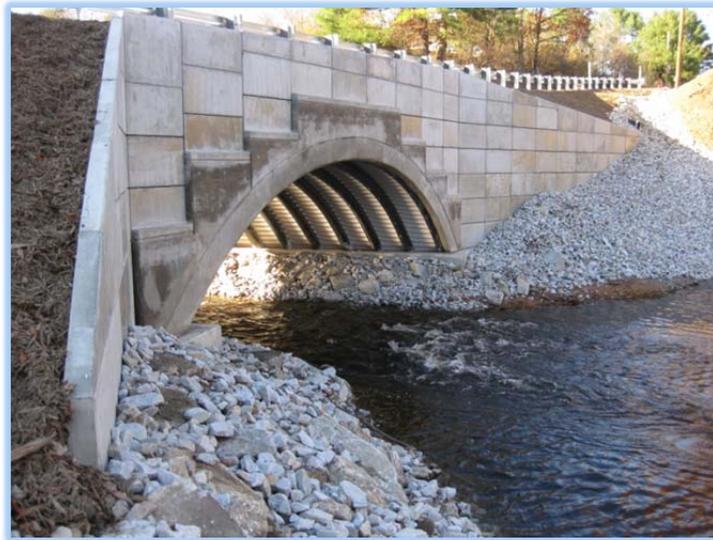
## Recommended Citation

Maine Transportation Research Division; Maine Department of Transportation; and Goslin, Keenan, "Bridge-in-a-Backpack™ Task 6: Guidelines for Long Term Inspection and Maintenance, 2016" (2016). *Transportation Documents*. 106.  
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# Transportation Research Division



## Technical Report 16-12

### *Bridge-in-a-Backpack™*

### *Task 6: Guidelines for Long Term Inspection and Maintenance*

Technical Report Documentation Page

1. Report No. ME 16-12	2.	3. Recipient's Accession No.	
4. Title and Subtitle Bridge-in-a-Backpack™ Task 6: Guidelines for Long Term Inspection and Maintenance		5. Report Date January 2016	
		6.	
7. Author(s) Keenan Goslin Scott Tomlinson		8. Performing Organization Report No. 15-34-1023F	
9. Performing Organization Name and Address University of Maine		10. Project/Task/Work Unit No. Project 17891.00	
		11. Contract © or Grant (G) No. Contract # 20111223*2878	
12. Sponsoring Organization Name and Address Maine Department of Transportation 16 State House Station Augusta, Maine 04333		13. Type of Report and Period Covered	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract (Limit 200 words)			
<p>This report includes fulfillment of Task 6 of a multi-task contract to further enhance concrete filled FRP tubes, or the Bridge in a Backpack. Task 6 provides guidelines for long term inspection and maintenance.</p> <p>This bridge consists of a buried arch system including structurally integrated stay-in-place concrete-filled fiber reinforced-polymer (FRP) tubes (CFFTs) as main structural members, an FRP or concrete deck, foundations, and headwalls holding back soil. The FRP composite tube, typically constructed of braided carbon-glass material within a vinyl ester resin (VE-based GFRP), provides a stay-in-place form for the concrete and tensile reinforcement as a structurally integrated part of the arch composite section. As such, the durability and structural performance of the FRP composite tube and its bond with the concrete throughout the design life are critical to the overall system durability. The FRP tube is exposed to both the environment on the exterior, and the concrete on the interior, and these dual exposure durability requirements must be taken into account during design, and carefully monitored through inspection during service life to detect damage or degradation that could impact strength or serviceability.</p>			
17. Document Analysis/Descriptors Concrete filled fiber reinforced polymer tubes, arch bridge, inspection guidelines		18. Availability Statement	
19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages 29	22. Price

**Bridge-in-a-Backpack™**  
**Task 6: Guidelines for Long Term Inspection and Maintenance**

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## Introduction

The University of Maine in collaboration with Advanced Infrastructure Technologies (AIT) and the Army Corp of Engineers has developed the Bridge-in-a-Backpack™ system. As Dagher et al [1] and Colgrove [2] describe, this Bridge-in-a-Backpack™ (BiaB) system consists of a buried arch bridge system including structurally integrated stay-in-place concrete-filled fiber-reinforced-polymer (FRP) tubes (CFFTs) as main structural members, an FRP or concrete deck, foundations, and headwalls holding back soil. Parts of a typical BiaB system are shown in Figure 1. The FRP composite tube, typically constructed of braided carbon-glass material within a vinylester resin (VE-based GFRP), provides a stay-in-place form for the concrete and tensile reinforcement as a structurally integrated part of the arch composite section. As such, the durability and structural performance of the FRP composite tube and its bond with the concrete throughout the design life are critical to the overall system durability. The FRP tube is exposed to both the environment on the exterior, and the concrete on the interior, and these dual exposure durability requirements must be taken into account during design, and carefully monitored through inspection during service life to detect damage or degradation that could impact strength or serviceability.

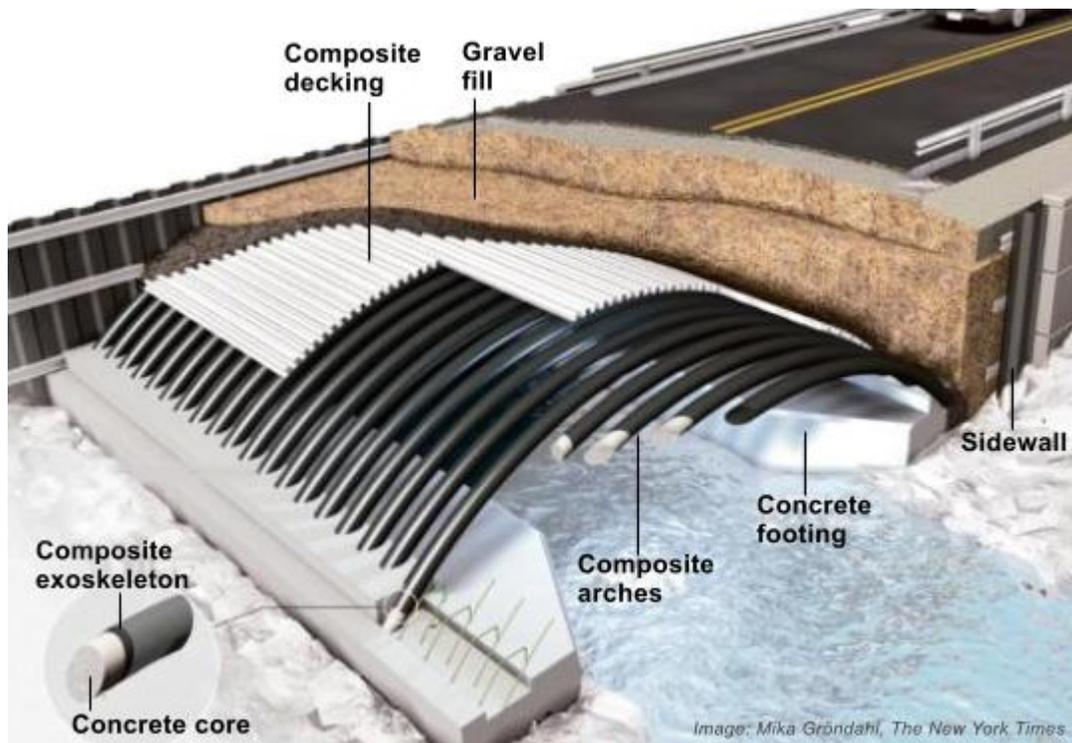


Figure 1: Typical Bridge in a Backpack System

This damage can come from many sources as the **BRIDGE INSPECTOR'S REFERENCE MANUAL**, Ryan et al [3], indicates, including: FRP fabrication imperfections, damage due to transportation and installation, voids during concrete placement, impact during service life, chemical exposure, moisture infiltration, thermal movements of the system, environmental exposure on the exterior, and as Demkowicz [4] describes, concrete alkaline exposure on the interior. A robust inspection program throughout the fabrication, installation, and service life is crucial to long-term performance of the system. Overall, the **BRIDGE INSPECTOR'S REFERENCE MANUAL**, Ryan et al [3], recommends the inspection program for FRP will look for: blistering, voids and delaminations, discoloration, wrinkling, fiber exposure, scratches, and cracking. This inspection program should include guidelines for: inspection procedures, frequency of inspections, qualifications of personnel, inspection reports, and maintenance of bridge inventory. The inspection procedures can include many methods at all stages including both destructive testing and non-destructive testing (NDT).

This report focuses on the first part of the inspection program, inspection procedures, and makes general recommendations based on existing Maine standards for other areas of the inspection program with differences for CFFT BiaB systems noted. First, the materials specific to the BiaB system are discussed, and specific reasons for post installation NDT are laid out. Next, the composite durability and environmental degradation factors already incorporated into the design of the system are discussed. Types of damage are then presented that are specific to FRP systems, along with areas of interest specific to BiaB systems. Specific methods of inspection, along with a summary of literature concerning their applicability and use with FRP products including BiaB, are given. These are broken into two parts: standard visual and physical inspection techniques, and advanced inspection techniques including thermography which the University of Maine has investigated as part of this study. Additional advanced inspection methods are discussed, and research conducted by the University of Maine in detecting delamination and voids is summarized. Recommendations are made for inspection procedures, frequency of inspections, qualifications of personnel, inspection reports, and maintenance of bridge inventory. Finally, overall conclusions concerning inspection of CFFT BiaB systems are given as well as recommendations for areas of future research into advanced inspection techniques.

## **Hybrid FRP Composite Materials**

As Dagher et al [1], Telang et al [5], and Ryan et al [3] discuss, Fiber Reinforced Polymer (FRP) composite materials are seeing increased use in civil infrastructure due to their durability, strength and weight. Composite materials have an almost infinite number of configurations. While initially the use of FRP focused on aerospace or automotive applications, cost reduction and advances in manufacturing techniques have allowed this increased use of FRP in civil infrastructure applications. These uses include strengthening or repair applications to existing infrastructure, use of replacement or new subcomponents such as bridge decks, and use in substructure components such as in timber/FRP glulam, and, as the focus of this report, in the CFFT BiaB system.

### ***Unique Aspects of the Bridge in a Backpack System***

The BiaB system uses a unique FRP layup consisting of a multilayer hybrid braided composite that consists of three layers. The inner layer is a braided E-glass fiber, and the two outer layers are carbon fiber. The resin utilized is a vinyl ester thermoset resin infused with a vacuum resin infusion process. The FRP tube is then filled from a single point in the top of the arch with self-consolidating concrete forming a CFFT arch. This type of construction presents unique limitations on inspection programs. The nature of the tube presents limited inspection accessibility to inside of the FRP Tube prior to concrete filling. Additionally, the concrete filling process presents limited inspection access during filling to ensure no voids are generated. Finally, the degradation of in-situ CFFTs is difficult to measure as opposed to other materials. For CFFTs there is no visible or measurable section loss, corrosion, or cracking as there is with steel or metals; there is no visual or measurable spalling or cracking as there is with concrete; and there is no visual rotting, section loss, or insect boring as with timber. This necessitates the use of more advanced inspection techniques.

### ***Composite Durability and Environmental Degradation Factors***

The study by Tomlinson et al [6] indicates similar VE-based GFRP systems to be satisfactory at or beyond 100-year design lives with approximately 70 to above 95% tensile and shear strength retention, which exceeds the current standard 0.65 environmental degradation factors for GFRP from the **AASHTO LRFD GUIDE SPECIFICATIONS FOR DESIGN OF CONCRETE-FILLED FRP TUBES FOR FLEXURAL AND AXIAL MEMBERS**, AASHTO [7]. Existing long-term durability experimentation results for VE-based braided E-Glass/Carbon fabric at standard laboratory conditions conducted by Demkowicz [4] have been compared to current research results using both ambient and accelerated conditioning procedures. Similar results are found for VE-GFRP materials across sources, showing little effect of accelerated conditioning protocols (ACPs) on modulus of elasticity, and similar percentage of retention strength values for similar ACPs and times. Ambient results were then compared to results in ACPs at elevated temperature.

This comparison shows a structure design life in excess of 100 years is achievable with environmental strength degradation factors ( $C_E$ ) ranging from 0.70 to 1.00 depending on the specific experimental methodology. These degradation factors could be conservative since they are based on completely submerged conditions, as it has been shown by Huang [8] that ambient relative humidity conditions could decrease the effect of the environmental durability factor and could cause the factors calculated to be conservative. Additionally, since the GFRP tubes fully encapsulate the concrete core and prevent the ingress of water, the GFRP tubes likely experience lower sustained alkalinity exposure than is assumed in other applications of GFRP where water may be present. Robert and Benmokrane [9] found that embedding a VE-based GFRP rod in mortar caused significantly less degradation than the traditional pore solution on bare bar. In summary, environmental degradation factors are taken into account during the design of FRP in CFFTs, and has been shown to be conservative for a 100 year design life.

## **Types of Damage**

There are several types of damage that should be considered when inspecting hybrid composite tubular arch bridges or similar structures. Ryan et al [3], recommends the inspection program for FRP will look for: blistering, voids and delaminations, discoloration, wrinkling, fiber exposure, scratches, and cracking.

### ***Blistering***

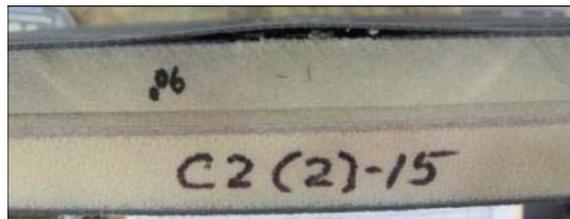
Ryan et al [3] describes blistering as “surface bubbles” caused by moisture trapped in the laminate during fabrication. Blisters could also form in service with CFFTs due to water movement through cracks and/or freeze/thaw cycling. Hong and Hastak [10] found blisters to be considered as a concern by the Ohio DOT of similar nature to delaminations or voids.

### ***Delamination & Voids***

Ryan et al [3] describes voids and delaminations are regions where the FRP shell or layers of the FRP shell have separated from each other. Voids could be present from construction when air pockets form between the concrete and FRP shell. Delaminations could be caused by impact, excessive flexure or poor quality control during manufacturing. Figure 2 shows a void and resulting surface crack of a foam filled FRP structure. Figure 3 shows a delamination due to a puncture.



**Figure 2: Voids resulting in surface cracks (Ryan et al [3])**

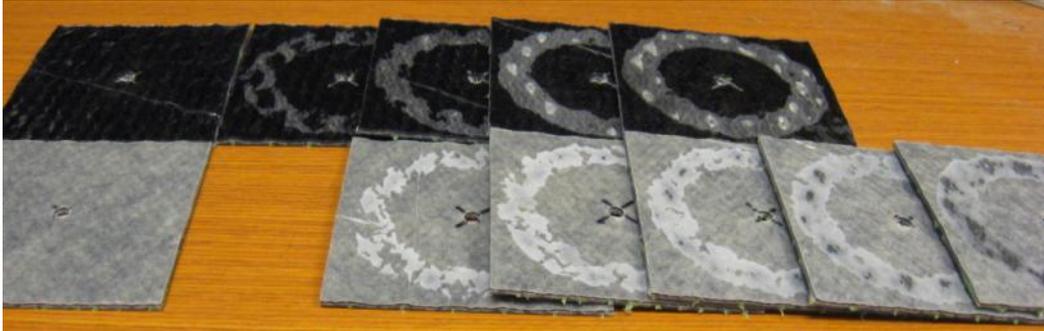


**Figure 3: Delamination due to puncture (Kittridge et al [11])**

Delaminations may be found with visual or physical examinations. Whitening may be present indicating cracks in the resin/matrix.

## ***Discoloration***

Discoloration may be indicative of structural problems. Whitening due to abrasion or excessive strain such as that seen in Figure 4 is detectable with visual inspection and can be minor or severe depending on the level of damage to the fibers.



**Figure 4: Discoloration due to abrasion, study samples**

As Ryan et al [3] describes, discoloration in FRP composites can also be due to environmental degradation, moisture infiltration, or chemical reactions due to contact with excessive UV, heat, or other chemicals. Previous testing by Demkowicz [4] for the hybrid composite arch bridge technology has shown there to be very little discoloration of the BiaB composite tubes caused by alkali, water, and salt water exposure.

## ***Punctures, Holes, Cracks***

According to the **BRIDGE INSPECTOR'S MANUAL**, Ryan et al [3], punctures, holes, and cracks may result from impact of vehicles, debris such as logs or rocks, or other deficiency left untreated. Full or partial punctures may result in additional cracking and delaminations. A puncture in a BiaB composite CFFT with a puncture can be seen in Figure 5. The damage shown in Figure 5 is quite small and not an immediate structural concern, but would need to be sealed with a small surface patch to prevent the ingress of water or chemicals and which could cause future degradation of the FRP.



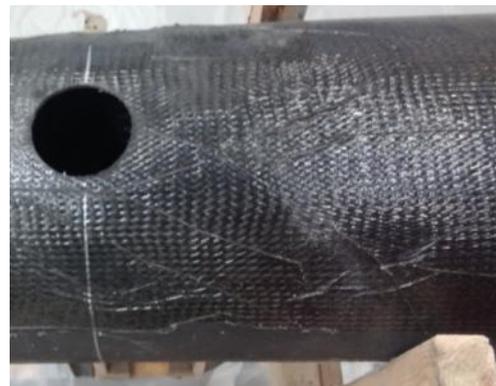
**Figure 5: Full puncture/hole in carbon fiber laminate**

### ***Wrinkling***

Wrinkling can occur in multiple areas of the FRP. This can occur in the fabric in the lamina itself, which is generally due to fabrication control issues, and is evaluated for acceptance prior to shipment of the FRP tube. Another type of wrinkling can occur in the bagging film as shown in Figure 6, causing a resin wrinkle as shown in Figure 7. This type of wrinkling is normal for this type of FRP tube structure and not a structural concern. Wrinkling can also be due to high compression stresses in a thin composite, which results in buckling of the tows or fibers. While tow buckling is certainly a sign of structural distress, it is highly unlikely that it would occur in a BiaB tube since the concrete carries the vast majority of the compressive stresses.



**Figure 6: Bagging film wrinkles acceptable in the resin layer of a BiaB FRP tube**



**Figure 7: Acceptable wrinkling in the resin layer of a BiaB FRP tube**

### ***Fiber Exposure***

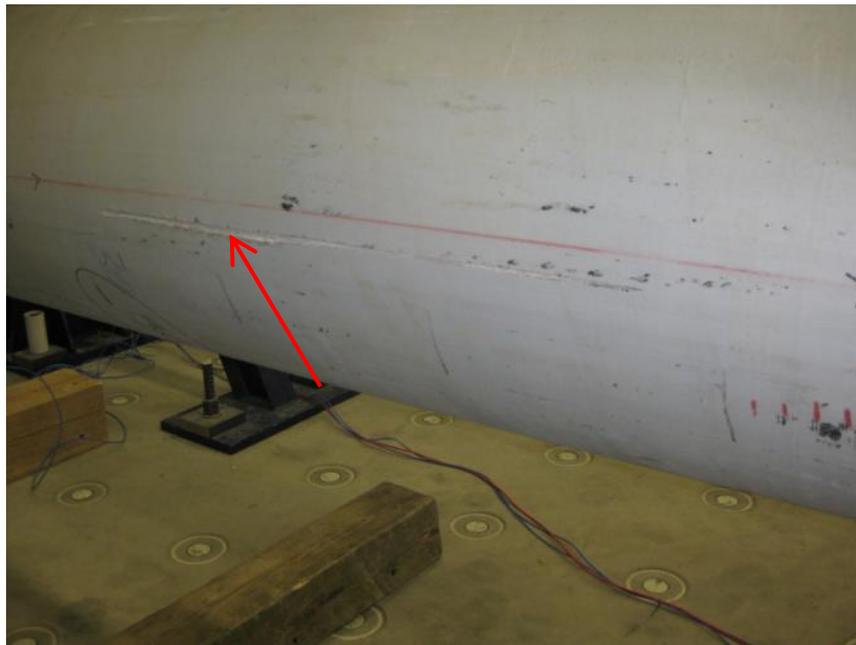
Fiber exposure often occurs along with other types of damage, such as punctures, abrasion, fire, or scratches and gouges. This is a serious condition due to the significant exposure to fibers and should be remedied. Along with the fiber exposure shown in Figure 2, Figure 4, Figure 5, Figure 9, and Figure 10, fiber exposure due to fire is shown in Figure 8.



**Figure 8: Fibers exposed due to fire damage**

### ***Scratches or Gouges***

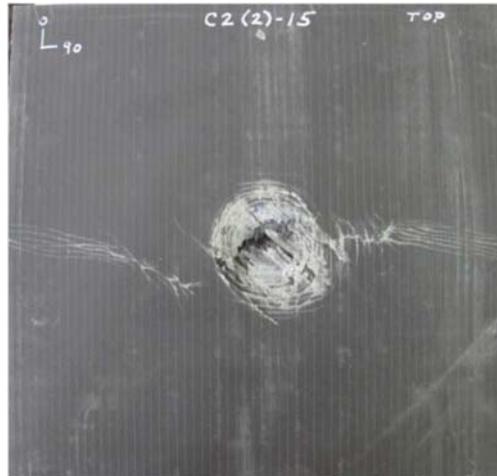
Scratches are generally seen in the surface of the FRP laminate and can be minor to severe. Severe scratches could develop into cracks where fibers are damaged or cut and cause structural concerns. Scratches could be caused by improper handling during erection or by vandalism once construction is completed. They will usually be detectable by visual inspection and may also be evident with delamination.



**Figure 9: Scratch in FRP pile**

## ***Cracks***

Cracks can form along with other types of damage, and can lead to fiber exposure. Major cracks should be repaired due to the possibility of decrease of structural capacity or exposure of fibers to damaging conditions. Cracks are shown around a puncture damage area in Figure 10.



**Figure 10: Cracks form around a puncture (Kittridge et al [11])**

## Typical Key Inspection Locations

Key locations for inspection of the tubular composite arches include the crown, shoulders (approximate quarter span), and bases of arch where they are embedded in the foundation. Dagher et al [1] has described these are the locations of peak moments and stresses. Additionally, any splices and connections to FRP headwalls and decking are areas to inspect. These areas are shown in Figure 11 and Figure 12.

1. Crown – area of peak moment. Look for distress, particularly discoloration due to excessive strain or excessive deflections
2. Shoulders – area of peak moment. Look for distress, particularly discoloration due to excessive strain or excessive deflections
3. Arch bases – area of peak axial load. Look for distress, particularly discoloration due to excessive strain or splitting of cross section or foundation
4. Splices (as applicable) – look for signs of increased separation of splice components, delaminations, cracks or other deficiencies.
5. Headwall and Deck connections (as applicable) – look for signs of increased separation of connection components, delaminations, cracks, punching or other deficiencies.

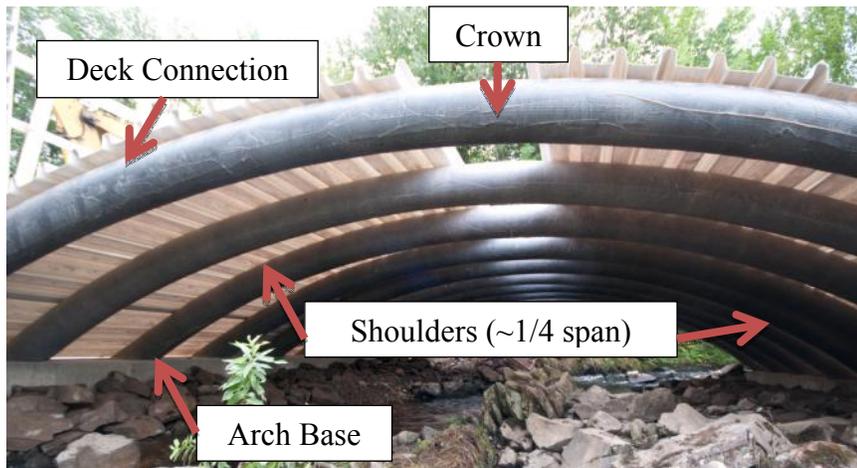


Figure 11: Typical key inspection locations, McGee Bridge under construction



Figure 12: Key inspection location, spliced arch in laboratory

## **Methods of Inspection**

There are three main methods of inspection: visual examination, physical examination and advanced inspection methods.

### ***Visual Examination***

According to the **BRIDGE INSPECTOR'S REFERENCE MANUAL**, Ryan et al [3], Visual examination is the primary inspection method for FRP composite structures. Standard inspection equipment in the **BRIDGE INSPECTOR'S REFERENCE MANUAL** [3] is needed. Depending on the location of the examination, a loaded test vehicle may be helpful in the visual examination to increase strain on the bridge components. This may help with seeing cracks or delaminations. The truck can be moved to various locations to maximize crack potential on individual members. However, due to the low allowed stresses for sustained and cyclic loading of 0.2 times the ultimate stress in **AASHTO LRFD GUIDE SPECIFICATIONS FOR DESIGN OF CONCRETE-FILLED FRP TUBES FOR FLEXURAL AND AXIAL MEMBERS** [7] and the mitigation of applied load effects through soil-structure interaction, use of a loaded vehicle will likely not be effective in helping identify cracking in BiaB arches.

### ***Physical Examination***

As described in the **BRIDGE INSPECTOR'S REFERENCE MANUAL** [3] physical examinations are performed by sounding or tapping on the structure. A small piece of steel rebar or similar object has accurately and easily found voids where accessible for several bridges. The change in sound from a sharp ringing to a dull thud will indicate delaminations or voids in the structure. Advanced inspection methods can then be used to determine the depth, size, and severity of the void.

## **Advanced Inspection Methods**

Advanced inspection methods include several technologies. Each technology has strengths and areas of usefulness. Some of these techniques include infrared (IR) thermography, ultrasonic testing (UT), microwave inspection methods, ground penetrating radar, acoustic emissions, and shearography. Thermography is a particularly promising technology for inspecting for voids in these tubular FRP composite structures, and is discussed in more detail herein. Other techniques are also discussed, and where applicable and/or promising, additional research is presented.

### ***Thermography***

Thermography uses an infrared (IR) camera to detect variations in temperature on the surface of an object or structure. Infrared thermography has been shown by Clark et al [12] to be a feasible method of finding reinforcing bar disbonding and spalling. In this study it was used to evaluate feasibility of detecting voids and delaminations mainly between the FRP shell and the concrete core of CFFT's in bridges. Many researchers including Alexis et al [13], Bagavathiappan et al [14], Brown and Hamilton [15], Kylili et al [16], Mabry et al [17], Mtenga et al [18], Starnes et al [19], and Taillade et al [20] have found that infrared thermography is an effective method for locating defects and disbonds between an outer FRP and inner concrete or masonry layer. This study built on this past research by focusing on CFFT's used in BiaB systems.

FRP tubes were fabricated with several types of artificial voids, and infrared thermography was used to evaluate different thermal loadings on the tube within the ability of the thermographic equipment to detect changes in temperature.

### ***Equipment***

As described by Kittridge et al [11], a FLIR SC620 infrared (IR) camera for conducting thermography inspections was used by the Composite Center. This portable camera along with the accompanying ExaminIR analysis software is a high performance IR system used for science and research applications. It has 640×480 resolution, a temperature range of -40°C to 500°C (-40°F to 932°F), accuracy of ±2°C (±3.6°F), 0.65 mrad spatial resolution, and a thermal sensitivity of ≤55 mK. Data (including full field radiometric temperature measurements) are captured either as still images or streaming video. Changes in heat transfer rate (and therefore surface temperature) due to internal flaws create an image that highlights various defects. A photograph of the SC620 is provided in Figure 13.



**Figure 13: Infrared camera in use**

### *Thermography Experimentation Methodology*

Four FRP tubes were manufactured with artificial voids. Passive and active methods were used to evaluate the feasibility of detecting those voids with the equipment on hand.

The specimens were 6.5 inch diameter hybrid glass/carbon fiber FRP tubes, nominally 6 feet long, with multiple artificial voids directly on the inside of the FRP shell. All tubes were mapped for actual locations, only two are marked on the exterior for locations of actual voids. To produce the voids several materials were used that included  $\frac{3}{4}$  inch Foamular 250 foam board insulation,  $\frac{1}{4}$  foam sill seal, and air pockets formed by sandwiching plastic film with tacky tape. Two different thicknesses of the plastic film air pocket were created. Various size foam blocks were used as well for simulating air voids between concrete and CFRP tube. These materials can be seen in Figure 14 prior to installation. The installed materials can be seen in one tube in Figure 15.



**Figure 14: Materials used to create artificial voids**



**Figure 15: Inside of tube with artificial voids**

Four experimentation methods, or situations, were used to evaluate IR thermography methods for their ability to detect the locations of the artificial voids in the FRP tubes. The first experimentation method was designed to use extreme temperature variations between FRP tubes in contact with inner materials compared to FRP not in contact with inner materials. This was used to evaluate the feasibility of the equipment for the task of identifying voids. This first method consisted of using insulation to create artificial voids and subsequently filling the tube with snow. This creation of an extreme temperature variation between the tube and a void confirmed the feasibility of the equipment for detecting voids, clearing the path forward for more detailed subsequent experimentation methods. The four experimentation methods utilized, including the first qualifying method, were:

1. Filling the tubes with snow
2. Filling the tubes with self-consolidating concrete (SCC) similar to field conditions
3. Place concrete filled tubes in sunlight to assess the effect of radiant heating on thermography results
4. Evaluate tubes left outside overnight for ability to see voids throughout the following day.

### **FRP Tubes: Filled with Snow**

Tubes were filled with snow by packing the snow lightly and tapping the bottom of the tube lightly on the ground by picking it up approximately 6 inches and dropping the plugged end on the ground. This was repeated until the tube was filled to desired level as seen in Figure 16 and Figure 17.



Figure 16: Filling tube with snow



Figure 17: Snow filled tube

Once filled the tubes were brought back inside the composites lab and placed in front of the FLIR 600 camera. Photographs were taken of surface temperatures at predetermined time intervals, recording the temperature variances on the outside surface of the CFRP tube as seen in Figure 18 and Figure 19.

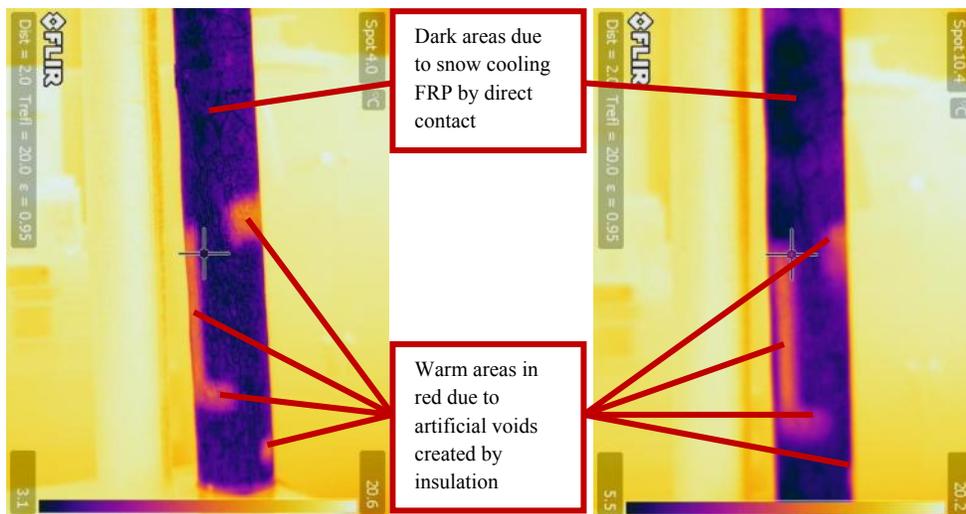


Figure 18: Snow filled tube inside

Figure 19: Snow filled tube inside

The first experimental methodology, which consisted of using snow to create extreme temperature differentials between FRP in contact with inner material and FRP not in contact with inner material due to voids, successfully showed voids in thermal images where placed. This success demonstrated the feasibility of the inspection technique.

### **CFFTs: Filled with Self-Consolidating Concrete – Laboratory Conditions**

A process similar to the experimentation of filling the tube with snow was used during the filling of the tubes with concrete. This process was intended to evaluate the feasibility of using IR thermography to observe the CFFT during the process of filling the tubes with concrete and being able to detect voids from a distance. Tubes were prepared by placing artificial voids

similarly to the snow experimentation. Tubes were then filled with SCC from batching for Task 4 of this project in the basement concrete lab in Boardman Hall.

Images are shown for one placement. Tube K was partially filled by hand starting at 11:40 on April 6, 2012. A series of images was taken after filling starting at 12:24 and continuing for roughly half an hour. The first is shown in Figure 20 and the last in Figure 21.



Figure 20: Partially filled Tube K, 12:24, time since filling ~30 minutes



Figure 21: Partially filled Tube K at 12:49, time since filling ~55 minutes

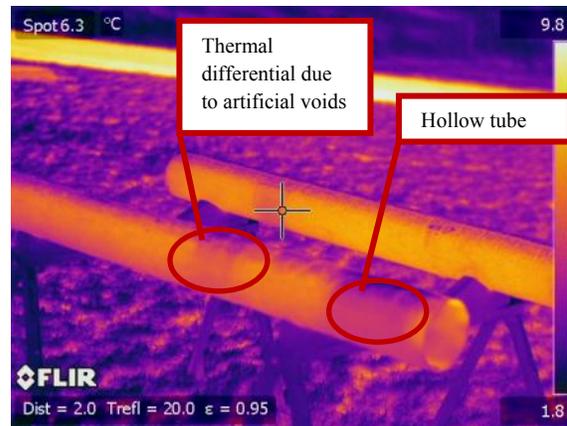
The IR thermography successfully detected the artificial void during filling, and was able to be detected in images ranging from half an hour after filling to an hour after filling. The ability to see the void was greatly diminished roughly an hour after concrete placement, but is still detectible as Figure 21 shows. Based on this experimentation, IR thermography could be used during concrete placement to successfully detect voids before the concrete has cured. This ability could be used to consolidate the concrete causing the void before curing, thus allowing defects to be removed while there is still opportunity to do very simply cost effectively.

### **CFFTs: Filled with Self-Consolidating Concrete with Voids – Exterior Conditions**

Concrete filled tubes were placed outside on several occasions for inspection with IR thermography. This simulated in place conditions for BiaB inspections. Various environmental conditions were evaluated including direct sunlight, overcast conditions and early and late day conditions with relatively rapid changes in ambient air temperature. Figure 22 shows the CFFTs outside of the laboratory for inspection. Tubes were checked for effects of thermal changes in air temperatures and direct radiation heating from the sun. As can be seen from the thermal photo in Figure 23, 2 voids were seen by their darker color indicating a temperature variance.



**Figure 22: Tubes outside of lab**



**Figure 23: Tubes inspected with IR**

It was difficult to detect the voids on sunny days where there was direct heating of the surface of the FRP as is shown in Figure 24.

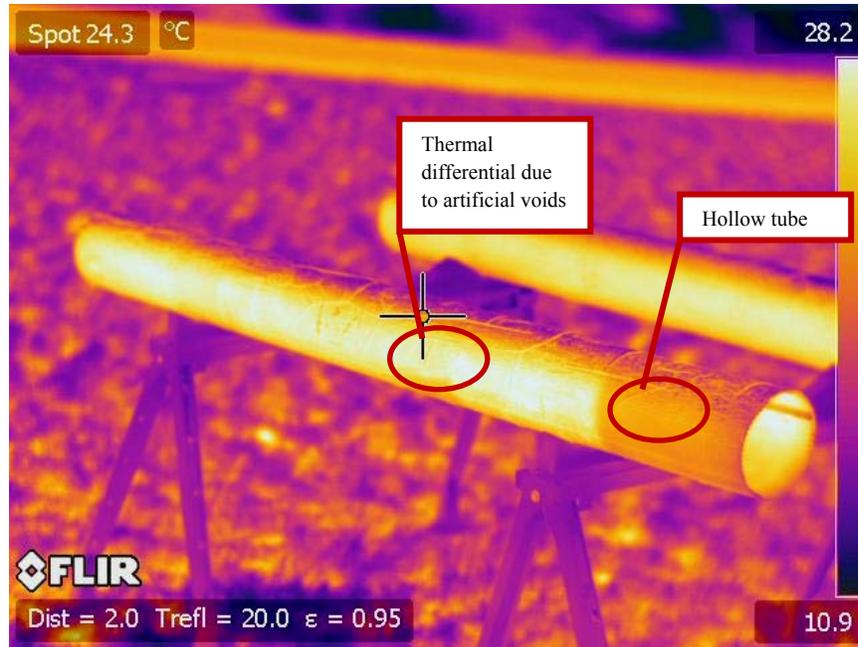


Figure 24: Tubes in direct sunlight

The best results for finding the voids came on overcast days with higher temperature variance from overnight to the mid-day as is shown in Figure 25.

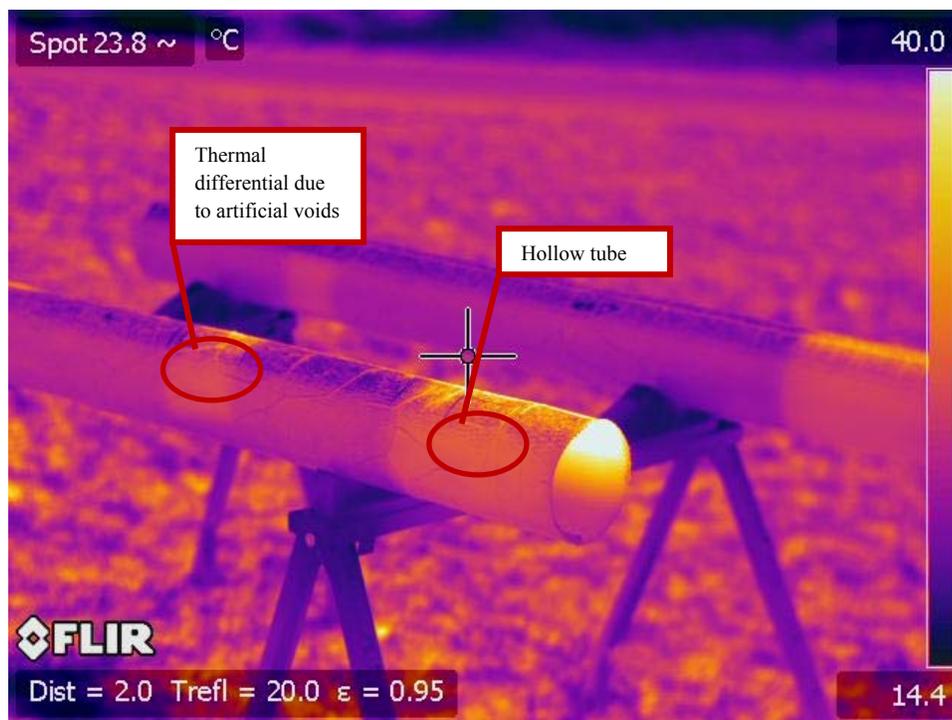


Figure 25: Tubes in cloudy skies

This experimentation IR thermography on CFFTs in exterior conditions shows the ability of the inspection methodology to detect voids in large field in various environmental conditions. The best detection occurred when large temperature differentials were present between the thermal mass of the concrete and exterior ambient temperature.

### *Conclusions from University of Maine Thermography Experimentation*

This method of introducing artificial voids between the CFRP Jacket and filler material was consistent with previous tests performed at other test facilities as Starnes et al [19] studied. Additionally, it appears the IR digital camera is a reasonable option for determining voids and possibly larger delaminations in FRP jacketed concrete. This option has been shown through this experimentation to be effective both during concrete filling and post-filling in ambient conditions. The best results were found during warm, overcast days following a cool night where the FRP over the void or delamination heats up more quick than the rest of the concrete filled tube.

### ***Microwave Inspection***

Akuthota et al [21] has shown microwave inspection of FRP wrapped mortar to be effective in determining both the size and severity of disbonds between CFRP and the mortar substrate. Feng et al [22] has also utilized microwave inspection to determine size and severity of disbonds between FRP jacketing used in seismic retrofit around concrete columns. They describe difficulties in their research, but overcame them with specialized focusing equipment. One such existing system is the Gap Mouse handheld unit [23] which offers real-time delamination, debond, and void detection for FRP/concrete structures.

Microwave technology, or electromagnetic (EM) imaging, can be used to determine debonding within concrete bridge decks by systems such as the High Speed Electromagnetic Roadway Measurement and Evaluation System (HERMES) [3]. While the HERMES system is not directly applicable to CFFTs, similar concepts such as multiple sensors and fast scanning rates over large areas could be used in future CFFT inspection programs. Research by Yu [24] and Büyüköztürk and Yu [25] has found that such systems using far-field EM technology can effectively find voids and disbonds in GFRP-concrete cylinders. This technology has strong potential to evaluate large areas very quickly in CFFT BiaB systems using far-field techniques, combined with handheld units to produce detailed analysis of smaller areas of focus.

### ***Ultrasonic NDT***

Ultrasonic testing (UT) has been found by Mirmiran and Wei [26] to be an effective advanced inspection technology for lifetime fatigue damage assessment of FRP encased concrete tubes. Additionally, work at the University of Maine by Kittridge et al [11] have found that UT provides an effective inspection method to detect defect depth within sandwich composite materials with voids and delaminations. Laser UT is discussed by Ryan et al [3] as a method

effective at determining not only the depth of voids and delaminations, but also the quality of the concrete within concrete members.

While this method is not ideal for finding defects on a large scale, once a defect is located with another inspection method, UT can be used to accurately determine the extent of the damage. This method can effectively measure the depth and extent of delaminations, debonds, and voids, as well as determine the quality of the concrete within the CFFT. Additionally, this method is the only one discussed with the possibility of determining the cumulative fatigue damage to CFFT structures with use over time which could be a significant advantage with additional validation.

## **Inspection Program**

In addition to inspection methods and procedures, additional aspects of the inspection program include the frequency of inspection, the qualifications of inspection personnel, inspection reports, and the maintenance of bridge inventory. These aspects with respect to CFFT and the BiaB system are discussed here.

### ***Frequency of Inspection***

Based on research presented in this report, there is no indication that the frequency of inspections should be modified from Maine [27] and the FHWA [3] standard two year inspection frequency.

### ***Qualifications of Personnel***

It is recommended that personnel inspecting CFFT BiaB systems have training beyond that of the standard bridge inspectors. For standard visual and physical examination a basic understanding of basic FRP manufacturing methods, composition, and mechanical properties; knowledge of common defects in FRP composites and how they affect FRP strength and durability; defects in FRP/concrete bonded interfaces; and FRP-specific inspection methods are required as a minimum.

For advanced NDT inspection techniques of CFFT, additional training beyond standard personnel qualification is recommended to effectively implement inspection programs and interpret results, as Telang et al [5] discuss and as described in the **BRIDGE INSPECTOR'S REFERENCE MANUAL** [3]. Many third party qualifications exist, such as the American Society for Nondestructive Testing [28] recommended by Telang et al [5] for FRP bridge decks, providing multiple levels of certification in advanced NDT techniques. These certifications specify levels of qualification and roles that the inspectors can have in quality control and quality assurance programs. For BiaB systems, this qualification should include training on composite materials and the inspection issues specific to FRP materials and FRP concrete interfaces. Similar qualifications have been successfully adopted for composite material inspection in the aerospace and shipping industries, and a similar set of third party training and certification is recommended to be implemented if advanced NDT inspection techniques such as thermography, shearography, microwave testing, or ultrasonic testing is to be used with CFFTs.

### ***Inspection Reports***

Inspection reports should address types of damage specific to CFFTs and BiaBs. These inspection reports should include: the type of damage seen, location of damage, inspection method utilized to locate the damage, and extent and severity of the damage. With advanced inspection techniques, prior inspection reports can be particularly useful to assess damage progression over the entire life of the bridge. One particular instance of this is using UT techniques to monitor fatigue damage to the internal concrete over the life of the bridge.

### ***Maintenance of Bridge Inventory***

In addition to legally required national and state requirements for bridge inventory, it is recommended that the bridge inspection records for CFFT and BiaB systems be made available to researchers for study and analysis regarding both short and long term trends. This data can be extremely valuable to validating models and code requirements concerning material and system performance over the life of the bridge.

## **Conclusions and Recommendations for Future Research**

CFFT BiaB systems present bridge inspectors with unique conditions compared with traditional materials. These conditions can be assessed using an understanding of the materials involved in the construction, the types of damage these materials can sustain, and the inspections methods best suited to damage detection. While the standard methods of inspection, visual and physical, remain the foundation of the inspection program, a robust inspection program can include advanced inspection methods to better detect underlying damage or degradation. These advanced inspection techniques can include infrared thermography, microwave inspection, ultrasonic testing, far-field radar, shearography, or a combination of several of these techniques. This study has shown thermography to be a fast, effective inspection technique to detect voids, delaminations, and debonds between the FRP and the concrete. This technique could add significant understanding to the underlying condition of the CFFT BiaB system.

One combination of advanced inspection techniques that other researchers, Taillade et al [20], have found to be effective with similar materials and geometries is infrared thermography combined with shearography. The full-field nature of infrared thermography combined with the highly sensitive damage severity measurements shearography offers is uniquely attractive to inspection of CFFTs. Expanding the scope of existing research from FRP on flat concrete in laboratory settings to concrete-filled FRP tubes in service could provide valuable inspection tools for BiaB systems.

Another combination of inspection techniques that could have significant impact on inspection techniques is far-field radar combined with hand-held microwave. Again, this combination of full-field inspection techniques provided by the far-field radar and the detailed severity information provided by the hand-held microwave unit provides clear information on the quantity of damage and the quality of the damaged sections. Expanding current research on FRP wrapped concrete to CFFTs could significantly impact BiaB inspection programs.

Finally, the use of UT as a detailed damage assessment inspection method is especially promising. As Mirmiran and Wei [26] found, through-thickness UT measurements could be used throughout the life of the structure to determine the quality of the concrete. Taking this research to the next level from simple laboratory specimen, validating it with experimental fatigue data of subcomponent CFFTs, and then verifying it with in-service bridges could provide a critical assessment tool for BiaB systems.

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