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Instrumentation and Monitoring of a New FRP Composite Bridge using Sensing Textiles

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Abstract

Fiber reinforced polymer (FRP) composite materials have been used in civil infrastructure systems as standard structural elements to mitigate the risk of steel corrosion in reinforced concrete and prestressed concrete structures. Recently, a new vehicluar bridge (Grist Mill Bridge, Hampden, Maine) using FRP composite materials as bridge girders is intrumented with sensing textiles to measure distributed temperture and strain data for long-term structural health monitoirng (SHM). In this paper, we report the design, preparation, laboratory testing, and field implementation of sensing textiles for instrumenting two girders of the new FRP composite bridge. In the design of sensing textiles for long-term SHM of bridges, distributed temperaure sensing and strain sensing using optical fibers were achieved by Brillouin Optical Time Domain Amplification (BOTDA). A layered structure in sensing textiles was proposed to protect optical fibers from environmental disturbances and to control the pattern of optical fibers during installation. A laboratory testbed (mockup bridge girder and installation cart) and an installation procedure were developed for efficient field installation of sensing textiles. From our laboratory and field test results, we demonstrated the field instrumentation of a distributed fiber optic sensor on a new FRP composite bridge through the pattern design of optical fiber cables, manufacturing of a laboratory testbed for trial installation, development of a field installation procedure, and field data collection. Through an academia-industry collaborative effort, such a field implementable technology can be further applied to existing civil infrastructures such as highway bridges, roadways, and tunnels.

Keywords: FRP Composite, Bridge Girders, Sensing Textiles, BOTDA

1. Introduction

Bridges are an essential compoment in transportation networks, as well as a valuable asset in civil infrastructure systems. Depending on the materials, structural system, environmental condition, and loading conditions (natural and manmade), bridges are vulnerable to different types of damages. They can age (materially) and deteriorate (structurally) at different rates. For example, concrete (reinforced concrete or RC and prestressed concrete or PC) bridges are vulnerable to the corrosion of steel members including reinforcing bars and prestressing strands, especially in aggressive environments where moisture, catalysts (usually chloride ions), temperature, oxygen, and acidity facilitate the electrochemical reactions (cathodic and anodic). Once corroded, steel members will start losing their cross sectional area for load bearing capacity. Consequently, corroded concrete bridges are prone to premature, brittle failures.

To mitigate the risk of steel corrosion, non-metallic/non-corrosive materials such as fiber reinforced polymer (FRP) materials have been used in civil infrastructure systems as standard structural elements. Glass FRP (GFRP) bars (ASTM 2022, ACI 2007, ACI 2022), GFRP rods (Bakis et al. 1998), and carbon FRP (CFRP) bars (ACI 2007, ACI 2022) were applied mostly for replacing steel rebars and for repairing in concrete bridges, while GFRP sheets/laminates (ACI 2017), CFRP sheets/laminates (ACI 2017, Yan et al. 2019) and CFRP strips (CSA 2022) were used for strengthening concrete beams, columns, piers, slabs, and walls. In such applications, FRP provides additional tensile strength, shear strength, and confinement (Ozbakkaloglu 2013) to strengthened members, but it is not considered as a major load bearing member.

In recent years, the use of FRP composites as a major load bearing member has been reported in the design of bridges. FRP composites have shown their promising advantages against tranditional structural materials (e.g., RC, PC, and steel) in bridge engineering, in view of their high strength-to-weight ratio, high endurance to fatigue, immunity to steel corrosion, enhanced durability against envrionmental attacks, flexible shapes in design, better quality controll in factory, accelerated construction, relatively-low maintenance, and lower life-cycle costs. Concrete-filled FRP tubes were used as bridge piers (Ozbakkaloglu 2013) without steel rebars. Pultrated FRP I-beams were used to connect concrete bridge decks in Spain (Mieres et al. 2007; Gutierrez et al. 2008). FRP composite bridge girders partially filled with foam and reinforced with transverse steel rebars were used in a bridge in Texas (Ziehl et al. 2009). Concrete-filled FRP tubes were also shaped as arches and used as bridge girders in Maine (Dagher et al. 2012; AASHTO 2012). FRP composite bridge girders used in bridge concrstruction were also reported in Poland (Siwowski et al. 2017). A new design of FRP composite bridge girders was recently implemented in a five-girder bridge in Hampden, Maine (Davids et al. 2022). Overall, most applications of FRP composites are in rebars for replacing steel, strips/sheets for repairing and strengthening, and laminates/wraps for providing confinement. Only limited applications of FRP composites have been reported in tub girders for bridge construction. In view of the novelty of FRP tub girders used in bridges, their long-term performance is of great interest to the civil engineering community.

There are three objectives in this bridge instrumentation; i) to collect distributed strain data using fiber optic sensors, ii) to better understand the long-term performance of FRP composite bridge girders, and iii) to examine the long-term durability of sensor installation. In this paper, we report the design, preparation, laboratory testing, and field implementation of sensing textiles for the instrumentation of a new FRP composite bridge in Hampden, ME. This research is a collaborative effort among the University of Massachusetts Lowell (UML), AIT Composites, Maine Department of Transportation (DOT), and the University of Maine (UMaine).

In the following sections, sensor design, development of intsallation plan, laboratory trial, field installation, sensor testing and calibration, and data interpretation will be described in detail.

2. Description of FRP Composite Girder Bridge

The bridge instrumented with sensing textiles is a 22.9-m (75-ft) vehicular bridge (Grist Mill Bridge) on the US Route 1A in Hampden, Maine, USA designed by AIT Composites and constructed by T Buck Construction, Inc for Maine DOT in 2020. The instrumented FRP composite girders were made by vaccum infusion using a female timber and polymer mold. The girders were made of a hybrid of E-glass and carbon FRP with Derakane 610c epoxy resin. There were five FRP composite bridge girders on the bridge. Figure 1 shows the location of the bridge. Figure 2 shows the layout of five FRP composite girders. Among the five FRP composite girders, Girders 1, 3, and 5 were selected for instrumentation.

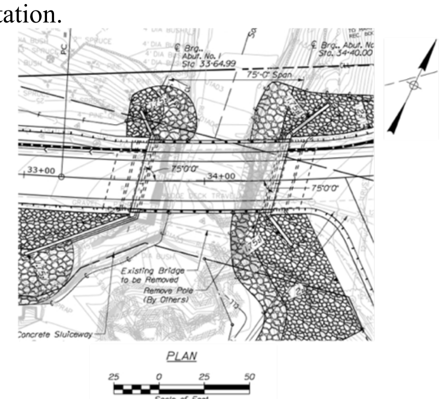


Figure 1. The Grist Mill Bridge, Hampden, Maine, USA. (Source: AIT Composites)

The FRP composite bridge girders have a width of 3'10" on the top and 1'5" (or 17") at the bottom. Their depth is 4'2". However, the inner width at the bottom is 18". Figure 3 shows the cross sectional dimensions of FRP composite girders. Further information regarding the design, manufacturing, and experiment assessment of FRP cmposite girders can be found in the literature (Davids et al. 2022; Davids et al. 2023).

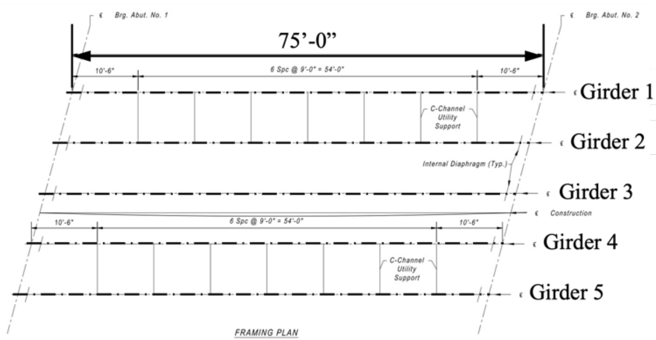


Figure 2. Layout of five FRP composite girders. (Source: AIT Composites)

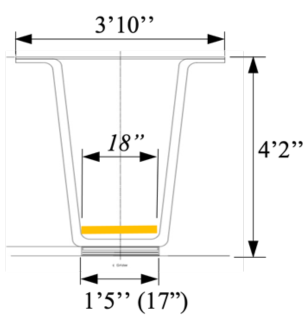


Figure 3. Cross section of FRP composite girders. (Source: AIT Composites)

3. Design and Manufacturing of Sensing Textiles

The sensing mechanism of sensing textiles is distributed temperature and mechanical strain sensing through Brillouin Optical Time Domain Amplification (BOTDA). The principle and application of using BOTDA for surface strain measurement can be found in our publication using pipe specimens and railway bridge as examples (Biondi et al. 2022; Biondi et al. 2023).

In the design of sensing textiles for bridge monitoring, the pattern of optical fibers needs to be oriented in the desired direction at selected locations. The reason in choosing a desired direction is for measuring certain strain component to be used in the structural health monitoring (SHM) algorithm of the structure. For these FRP composite bridge girders, our objective is to use distributed longitudinal strain measurements to calculate the stiffness of the girders for SHM purposes. The following sections describe the layered structure of installed sensing textiles for long-term SHM and the pattern design of optical fibers inside the sensing textile for strain measurement.

3.1 Layered Structure of Installed Sensing Textiles

To achieve long-term bridge monitoring in New England, the installed sensors must be durable in order to survive the severe local weather condition such as drastic seasonal temperature variation (e.g., from 95ºF in the summertime to -8ºF in the wintertime in Masachusetts). We proposed a layered structure for the installation of sensing textiles as shown in Figure 4.

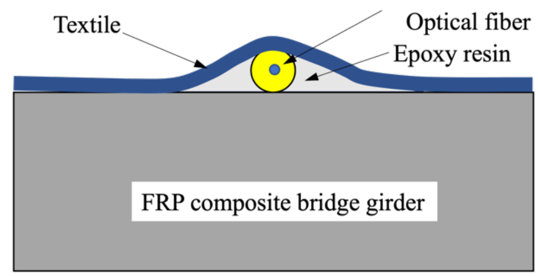


Figure 4. Layered structure of sensing textiles

In Figure 4, optical fibers are first stitched to the weaved textile at the designed pattern to form a sensing textile. When installing the sensing textile onto the surface of FRP composite bridge girders, the sensing textile is surmerged into an epoxy resin to make sure that the entire surface of the sensing textile can provide adhesion with the surface of FRP composite. To better protect optical fibers from an outdoor environment and to hold optical fibers at the installed location for a long time, optical fibers are placed between the textile and the surface of FRP composite to form a layered structure of installed sensing textiles. In this design, the triangular gaps adjacent to an optical fiber must be filled up with expoxy resin to avoid the formation of air pockets from happening. When installing sensing textiles, a paint roller is used to apply pressure on sensing textiles to remove or eliminate air pockets.

3.2 Pattern Design of Optical Fiber Cables

In the pattern design of optical fibers for sensing textiles, the major function of a structure is identified at first. The second factor to consider is the design of SHM algorithms. In the design of an SHM algorithm based on structural mechanics, health-related parameters are usually extracted or calculated from experimentally measurments such as displacement, velocity, acceleration, or strain. In our case, we used distributed longitudinal strain as the experimental measurement in our SHM algorithm. Two types of optical fibers were used for temperature and strain measurements; SMF-28e+ and 62.5/125 GIOF (Graded-Index Optical Fiber). One SMF-28e+ optical fiber cable was used for DTS (distributed temperature sensing). One multimode 62.5/125 GIOF optical fiber cable was used for distributed temperature and strain sensing based on BOTDA. Table 1 provides the technical specs of these two optical fiber cables.

Table 1. Specs of used optical fiber cables.

Fiber type	Temp. range (°C)	Mandrel radius (mm)	Outer diam. (μm)	Tensile stress (ksi)
SMF-28e+	-60 ~ 80	25	245	≥ 100
62.5/125 GIOF	-60 ~ 80	≥ 17	245	≥ 100

On the pattern design of optical fibers, a 74’ (length) by 18’ (width) textile was used to house two optical fiber cables configured along the longitudinal direction of the FRP composibe bridge girders. Eight strain gauges were also installed adjacent to the 62.5/125 GIOF optical fiber cable to calibrate distributed strain measurement. A U-shape pattern is used for both optical fiber cables, in which the first half (Section 1) and the second half (Section 2) sections of each cable can provide sufficient amount of data for our future analysis. In the event of optical fiber breakage during either girder transportation or bridge installation or long-term deterioration, the U-shape pattern would allow us to switch the launching end with the termination end in order to collect the maximum of data possible from installed sensing textiles. At the beginning and the end of the sensing textile, there were two 20-m long laching and termination cables for signal conditioning purposes. Figure 5 illustrates the U-shape pattern of optical fiber cables designed in the sensing textiles to measure distributed longitudinal strains of Girders 3 and 5.

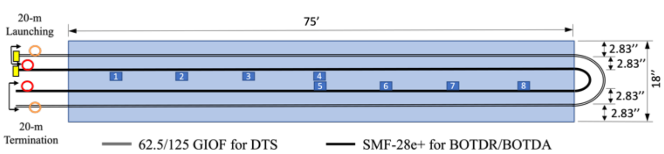


Figure 5. Pattern of optical fiber cables.

It should be noted that, in order to connect sensing textiles to the optical fiber sensing equipment at a distant location, additional length of optical fibers and strain gauge wires must be considered in the desitn.

3.3 Manufacturing of Sensing Textiles

Once the pattern design of optical fiber cables was completed, manufacturing of sensing textiles is carried out by an electronic crochet knitting machine (Comez Testronic 1600) located at Saint-Gobain Research North America (Northborough, MA). This knitting machine can produce a wide range of bouclé, plain and openwork knitted fabrics, and sensing textiles with embedded optical fiber cables. Figure 6 shows the machines located in the facility of Saint-Gobain Research North America.

Figure 6. Comez Testronic 1600 machine at Saint-Gobain Research North America.

During the manufacturing of sensing textiles, optical fiber cables were embedded by knitting optical fiber cables onto the substrate fabric with stitches at a given design pattern controlled by the electronic crochet knitting machine. After the optical fiber cables were embedded into the substrate fabric, eight small openings were manually made on the substrate fabric for future installation of strain gauges. Both strain gaues and their associated wires were temporarily fixed on the substrate fabric for the ease of transportation and installation. Figure 7 shows a portion of sensing textiles with embedded SMF-28e+ and 62.5/125 GIOF optical fiber cables. Figure 8 shows a fixed strain gauge with its wires temporarily fixed on sensing textile with blue tapes.

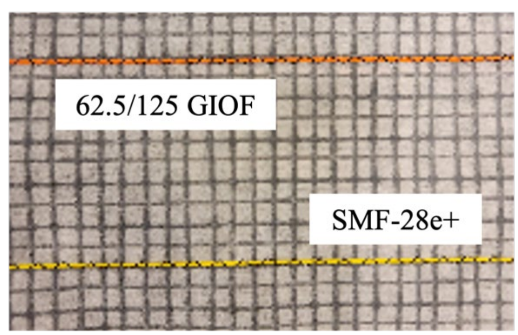


Figure 7. Embedded SMF-28e+ (orange) and 62.5/125 GIOF (yellow) optical fiber cables on the sensing textile.

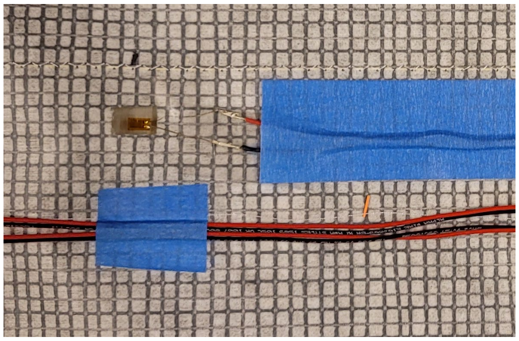


Figure 8. Fixed strain gauge and its wires on sensing textile.

Transporting a 74'-long sensing textile with a number of wire bundles attached requires proper packaging. We decided to fold sensing textiles around themselves into rolls for the ease of transport. Figure 9 shows a roll-up sensing textile with a bundle of extra length of optical fibers and a spool of extral wires for strain gauges. One roll was prepared for an FRP composite bridge girder.

Figure 9. Manufactured sensing textile in a roll.

4. Laboratory Testbed for Trial Installation

4.1 Selection and Deployment of Epoxy

In the installation of sensing textiles on FRP composite bridge girders, strong adhesives capable of resisting chemicals and water infiltration are needed since the installation of sensing textiles is designed to be permanent. A two-agent epoxy (105A epoxy resin and 206A slow epoxy hardener, West System) was selected from our previous laboratory experimentation on various types of adhesives with sensing textiles. However, preparation of this two-agent epoxy requires several minutes (depending on the volume) of mixing and 10 to 15 hours of curing time once deployed. In view of the surface area (108 ft^2 per girder, 216 ft^2 in total) to cover and the need to entirely submerge sensing textiles in epoxy, an amount of 0.546 gallon of epoxy was estimated. With a conservative percentage of loss (10~15%) during epoxy mixing and transportation, a total amount of 0.628 gallon of epoxy was obtained for this installation.

It is noteworthy to point out that, to avoid early curing and loss of viscocity of epoxy in an open, outdoor environment, we should mix two agents of epoxy at an proper amount to be consumed in 15~25 minutes. We might loss the design quality of epoxy if the mixed epoxy was left unused for too long (e.g., more than 30 minutes). Since we would not be able rapidly deploy epoxy to the entire surface area of FRP composite bridge girders, we would need to gradually mix a small portion of epoxy and deploy only that portion of epoxy. Epoxy was deployed by using paint brushes.

While depolying epoxy inside a confined space like FRP composite bridge girders, air ventilation and respiratory protection (OSHA 29 CFR 1910.134) must be provided. We used one portable industrial fan (supplied by AIT Composites) at the end of FRP tub girder to blow fresh air into the girder to improve the air circulation inside the girder. The installer also wore a respirator (3M 6503QL) with a cartridge (3M P100) for lung protection, a safety google for eye protection, and a pair of silicone gloves for skin protection as necessary personal protection equipment (PPE).

Furthermore, the confined space inside the FRP composite bridge girders also prohibited the installer from re-arranging or organizing sensing textiles inside the FRP composite bridge girders. It was expected that the installer can only deploy sensing textiles by unrolling the sensing textile rolls in one direction, considering the fact that the surface of FRP bottom flanges was covered by uncured epoxy.

4.2 Mockup Bridge Girder

Since this was our first instrumentation on FRP composite bridge girders in the field using sensing textiles, we built a laboratory testbed to detect and eliminate potential issues arising from field installation. This laboratory testbed was comprised of a mockup brige girder with actual cross sectional dimensions and a custom-built installation cart for installing sensing textiles. This testbed was necessary for us to develop a feasible, efficient installation procedure with the minimum manpower working inside the FRP composite bridge girders.

The FRP composite bridge girders to be instrumented have a trapezoidal cross section with a height of approximately 4', an upper base of 26" and a lower base of 18". The small cross sectional area prevented two people from working at the same location. It was even too small for a person greater than average size to easily maneuver inside the FRP composite bridge girder. Therefore, a one-person (installer) installation scheme was decided. To prepare the installer for navigating along the FRP composite bridge girder, a full-size mockup bridge girder was designed and built as shown in Figure 10.

(a) FRP composite bridge girder (b) Lab mockup girder
Figure 10. FRP composite bridge girder and lab mockup.

Two styrofoam panels (1" thickness) made of extruded polystyrene (Foamular NGX, Owens Corning) as the side walls and one polyisocyanurate panel (2" thickness, Super TUFF-R) as the bottom flange were used, as shown in Figure 10 (b). These panels were connected by styrofoam glue and reinforced by heavy-duty waterproof duct tape to maintain a stronger hold.

Once the mockup girder was completed, the installer used it to practice performing various tasks including deploying epoxy and installing sensing textile. To move from one location to another inside the FRP composite bridge girder, the installer would need a device to reduce his level of physical fatigue and to improve his mobility with logistic support to supply epoxy. Therefore, an installation cart was designed and built.

4.3 Installation Cart

To order to improve the mobility of the installer, a multi-functional installation cart was designed with the following main functions:

1) To reduce the physical fatigue of the installer during the installation process by providing a seating area – A two-layer cushion was installed at one end of the cart.
2) To serve as a receiving point for a bucket of epoxy transported by the rest of the team – One pulley was installed.
3) To mobilize the installer and physically connect the installer with the rest of the team to allow the rest of the team to pull the cart in one direction – Four pneumatic rigid casters with breaks, a pulley, and a polyester rope were installed.
4) To provide a temporary storage spage of tools for the installer – A storage area was preseved at the other end of the cart.

Figure 11 illustrates our design of the installation cart. In Figure 11, an epoxy container is connected to the close-loop polyester rope. It should be noted that the installation cart was operated by the rest of the team outside the FRP tub girder, rather than by the installer. Nonetheless, the installer can still move the cart in an emergency.

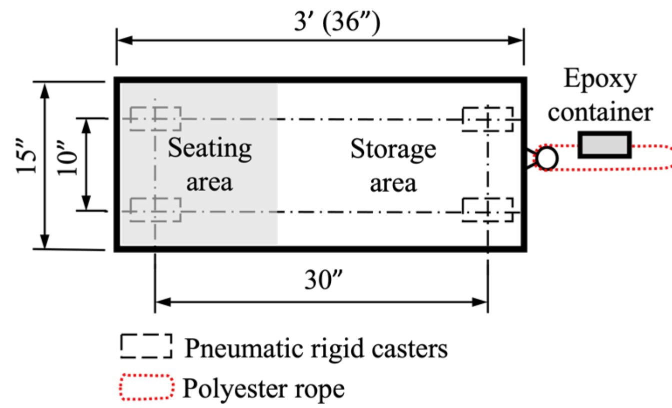


Figure 11. Design of installation cart.

Our design to move the installation cart and to transport epoxy (through an epoxy container) was by selectively pulling different numbers of the rope. When moving the installation cart, the close-loop rope is treated as one rope and pulled in one direction. Since the installation can only move in one direction (the other direction is uncured epoxy), we only need to use the rope as a cable constantly under tension. When transporting epoxy from ourside the tub girder to the installer inside the tub girder, the close-loop rope is treated as a ring cable and operated in two different directions; clockwise and counterclockwise. In the design shown in Figure 11, rolling the rope in the clockwise direction will transport the epoxy container from the installer to the rest of the team outside the tub girder. In other words, rolling the rope in the counterclockwise direction will bring the epoxy container from outside the tub girder to the installer. This way, we use one close-loop rope to provide two functions in the design of this installation cart.

Figure 12 shows the two-layer cushion on the cart. Figure 13 shows the custom-built installation cart.

Figure 12. Two-layer cushion on installation cart.

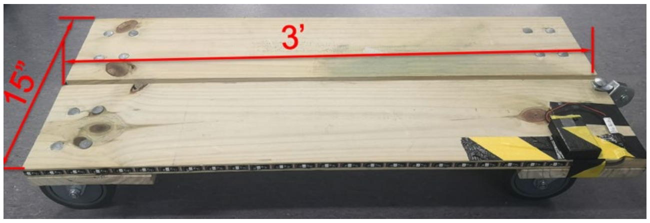


Figure 13. Installation cart.

Formation of an installation team is described in the following section.

4.4 Formation of the Installation Team

An installation team comprised of at least four members was designed for this instrumentation. Their responsibilities are described in the following:

- Installer: Responsible for i) deploying epoxy, ii) unrolling and installing sensing textile, iii) compacting the sensing textile to remove air pockets trapped between the sensing textile and the surface of FRP tub girder, and iv) communicating with the rest of the team for any needs (e.g., advancing the cart, requesting for epoxy supply). The installer is equipped with one unit of walkie-talkies for communication, a headlamp for better illumination, and one raspirator
- Cart operator: Responsible for i) pulling the installation cart toward the outside direction of the tub girder, ii) transporting additional expoy through moving the epoxy container, and iii) communicating with the installer. The carr operator is equipped with one unit of walkie-talkies.
- Epoxy mixer: Responsible for i) mixing the two agents of epoxy to make sure the epoxy is uniformly mixed, and ii) monitoring the idle time of epoxy to make sure it will be used within 10 minutes from mixing.
- Team captian: Responsible for i) documenting the starting time and ending time of each installation, ii) measuring the ambient temperature, iii) reminding other team members with any possible issues that may occur, and iv) communicating with other companies and state DOTs in case the installation has to stop.

4.5 Installation Procedure

We proposed a backward advancing scheme with the following installation steps for the instrumentation of FRP composite bridge girders.

1) Place the sensing textile roll, the installation cart, and a small portion of mixed epoxy on the cart with tools (e.g., paint brushes, walkie-talkie). The installer enters the FRP tub girder by siting on the cart and wearing required PPE. An industrial fan is turned on. Wireless communication using walkie-talkies is tested.
2) The epoxy mixer prepares a small portion of epoxy and transports to the installer through the epoxy container. Upon receiving the epoxy container, the installer starts deploying epoxy onto the surface of FRP tub girder.
3) After deploying epoxy, the installer unrolls the sensing textile roll and installs it over the surface area covered by uncured epoxy. The installer compresses the sensing textile to remove air pockets trapped underneath the sensing textile.
4) The installer informs the cart operator to advance the cart to the next position and the epoxy mixer to supply more epoxy.
5) Repeat Steps 2) to 4) until the installer completes installing the FRP tub girder.
6) Once one FRP tub girder is completed, the installation team moves to the next girder and repeat Steps 1) to 5).
7) After all FRP composite bridge girders are instrumented, the sensors are tested for their integrity and quality.

Figure 14 illustrates the installation procedure in which the installer moves backward in order to unroll sensing textiles in front of him.

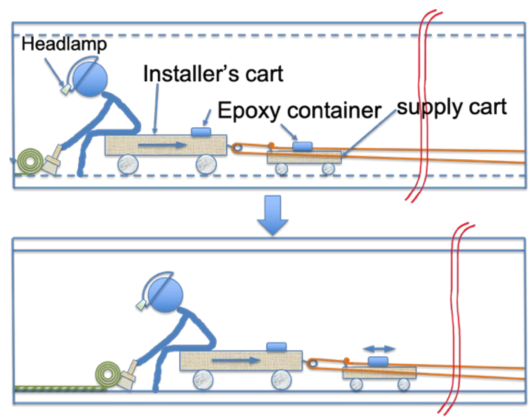


Figure 14. Backward advancing scheme.

5. Field Instrumentation

5.1 Installation of Sensing Textiles

Three FRP composite bridge girders were intrumented on October 6, 2020 in the parking lot of AIT Composites (Brewer, ME), where all FRP composite bridge girders were temporarily stored before construction. A power generator was provided by AIT Composites. Figure 15 shows the UML installation team and five FRP composite bridge girders. Figure 16 shows one installation cart and three sensing textile rolls.

Before we started installing sensing textiles, we noticed that the bottom surface of FRP composite bridge girders was covered in dust and not ready for epoxy deployment. After using a leaf blower to clean the composite surface, we used wet cleaning cloths to further remove any stains or mud from the composite surface. The leaf blower was used again to dry up the surface. Figure 17 (a) shows one UML student cleaning the surface using a leaf blower.

Figure 15. The UML team and five FRP composite bridge girders in Brewer, ME.

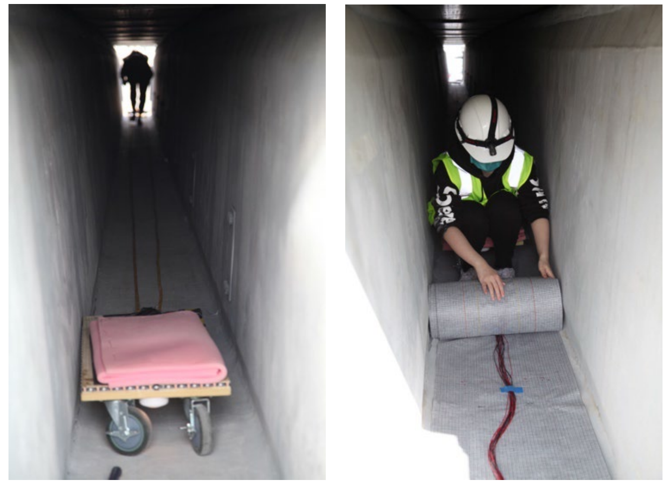
Figure 16. Installation cart and three sensing textile rolls.

(a) Surface cleaning. (b) After cleaning.

Figure 17. The UML team and five FRP composite bridge girders in Brewer, ME.

After the surface was cleaned, we started the installation procedure as shown in Figures 18 (Step 1) and 19 (Steps 2 to 4).

Figures 20 and 21 shows the instrumented FRP composite bridge girder (Steps 5 and 6). After installation, the baseline data of fiber optic sensors and strain gauges were collected on October 6, 2020, to make sure all installed sensors are intact, even though the epoxy was still uncured.



(a) Installation cart. (b) Unrolling sensing textile.

Figure 18. Installation procedure – Step 1).

(a) Deploying textile. (b) Mixing epoxy.

Figure 19. Installation procedure – Steps 2) ~ 4).

(a) Installed textile. (b) Epoxy container.

Figure 20. Installation procedure – Step 5).

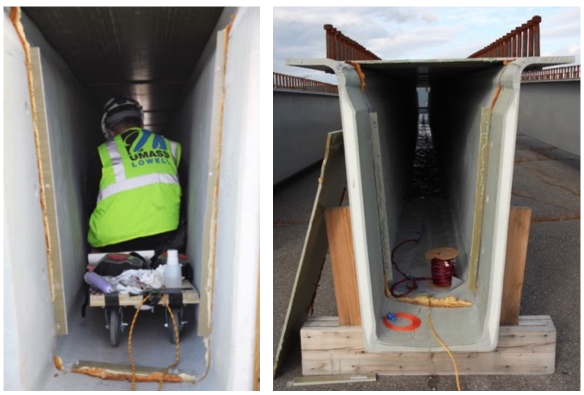


Figure 21. Instrumented procedure – Steps 5) and 6).

After 28 days of installtion, we returned to the FRP composite bridge girders in Brewer, ME on November 3, 2020, when we believe the epoxy was completed cured. The objective of this visit was to examine the quality of installation and to collect data collection was to test the integrity of installed sensing textiles. Figure 22 shows two instrumented FRP composite bridge girders at the parking lot at AIT Composites (Brewer, ME).

Figure 22. Instrumented FRP composite bridge girders

4.2 Sensor Testing and Calibration

On November 3, 2020, we used a laser source to test the integrity of optical fibers embedded in sensing textiles and found out that all signal strengths are strong. Figure 23 shows our signal strength test in the field using the equipment shown in Figure 24.

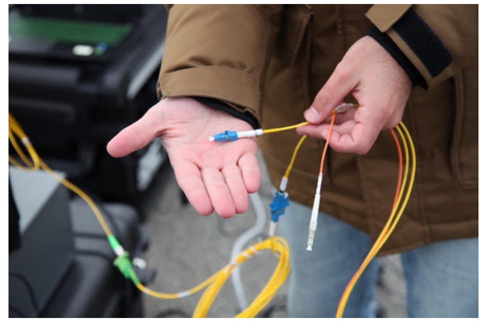


Figure 23. Signal strength test using a laser source.

Figure 24. Optical fiber sensing equipment.

After collecting the baseline data, we also re-arranged the additional length of optical fibers and wires by using heavy-duty duck tapes. Figure 25 shows Girders 3 and 5 after instrumentation. Figure 26 shows the constructed bridge.

Figure 25. Instrumented FRP composite girders 3 and 5.

Figure 26. Constructed Grist Mill Bridge.

Distribued longitudinal strain measurements collected on October 6 and November 3, 2020 are illustrated in Figures 27 and 28, respectively. In Figure 27, one spike of longitudinal strain in Section 1 of Girder 3 is found due to the accidental streching of opfical fiber cable during installation before the epoxy resin was fully cured. In Figure 28, another spike in Section 2 of Girder 1 is found during epoxy curing. After substracting the distributed strain data on October 6 from the one on November 3, we obtained the distrubuted strain difference on girders 1 and 3 to illustrate the effect of epoxy curing. Figure 29 will be used as the baseline in our data analysis for SHM of the bridge.

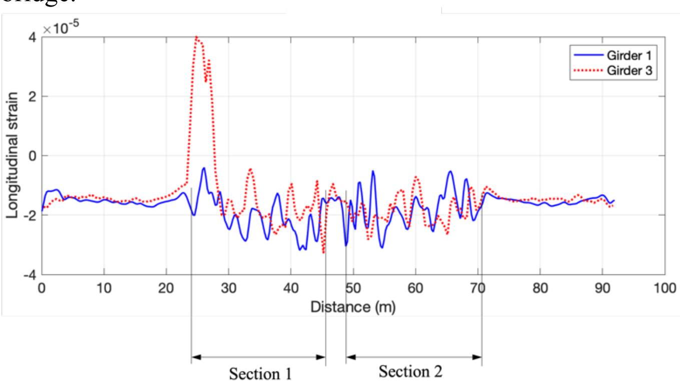


Figure 27. Instrumented FRP composite girders 1 and 3 on 10/06/20 with uncured epoxy.

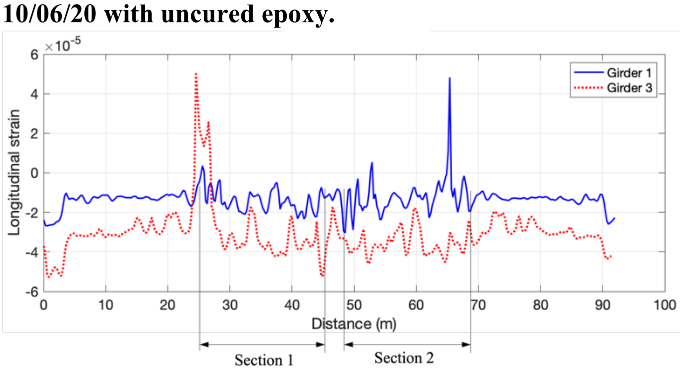


Figure 28. Instrumented FRP composite girders 1 and 3 on 11/03/20 with cured epoxy.

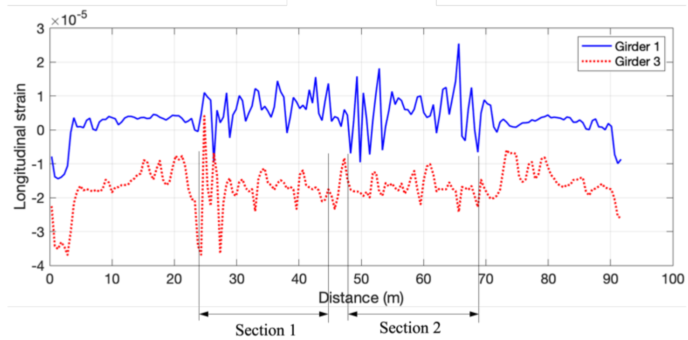


Figure 29. Distributed strain difference on girders 1 and 3 – The epoxy curing effect.

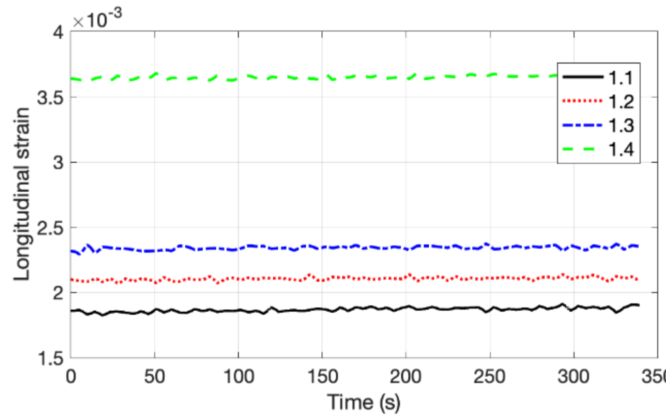


Figure 30. Strain gauge measurements on Girder 1 – 1.1 to 1.4 on October 6, 2020.

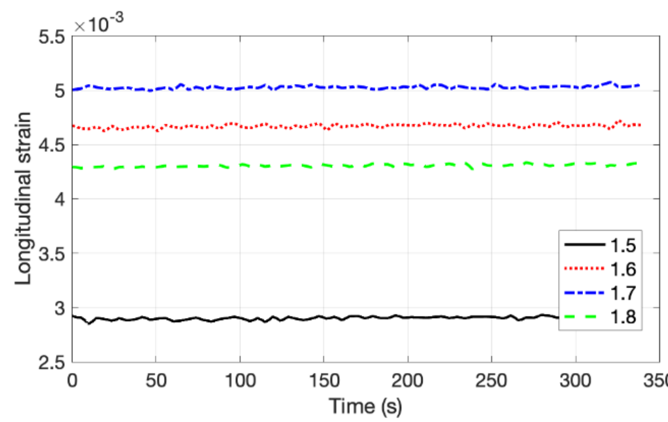


Figure 31. Strain gauge measurements on Girder 1 – 1.5 to 1.8 on October 6, 2020.

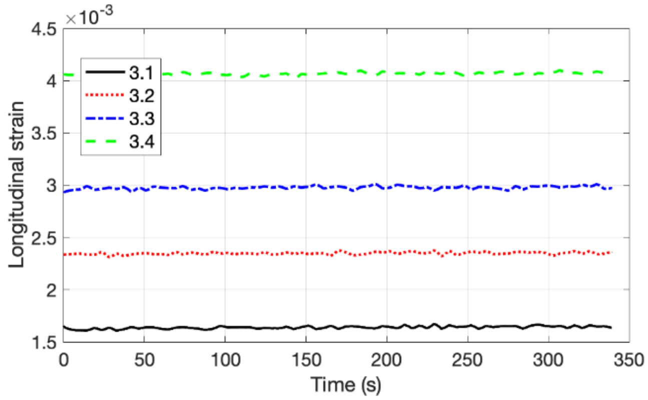


Figure 32. Strain gauge measurements on Girder 3 – 3.1 to 3.4 on October 6, 2020.

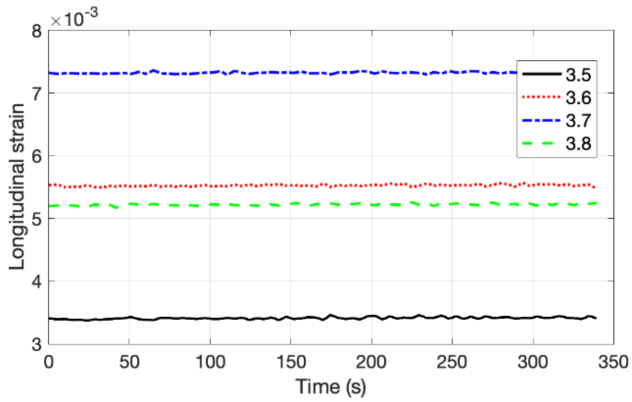


Figure 33. Strain gauge measurements on Girder 3 – 3.5 to 3.8 on October 6, 2020.

Figures 30 to 33 show the strain gauge time-history curves for 340 seconds from Girders 1 and 3, collected on October 6, 2020. From these longitudinal strain measurements, we can see the stability in the performance of sixteen installed strain gauges. The values of these strain curves will be used as the baseline values for future load tests on the bridge. The strain gauge curves collected on November 3, 2020, look similar to the ones in Figure 30 to 33.

6. Conclusion

In this paper, we reported our research activities on the instrumentation of a new FRP composite bridge through our laboratory and field efforts on the pattern design of optical fiber cables, manufacturing of a laboratory testbed (a mockup bridge girder and an installation cart) for trial installation, development of a field installation procedure, and field data collection. It is through this academia-industry-government collaborative project that we have demonstrated the practicality and feasibility of distributed sensing on bridges. Such a distributed sensing technology utilizing surface strains can be potentailly applied to other existing critical civil infrastructure systems like roadways and tunnels.

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References

AASHTO (American Association of State Highway and Transportation Officials). (2012). LRFD Guide Specifications for Design of Concrete-Filled FRP Tubes for Flexural and Axial Members. Washington DC.

ACI (American Concrete Institute). (1989). Building code requirement for reinforced concrete. ACI 318-89. Farmington Hills, MI: ACI.

ACI. (2007). Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures. ACI PRC-440-07. Farmington Hills, MI: ACI.

ACI. (2022). Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary. ACI CODE 440.11-22. Farmington Hills, MI: ACI.

ACI. (2017). Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. ACI PRC-440.2-17. Farmington Hills, MI: ACI.

ASTM (American Society for Testing and Materials). (2022). Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement, ASTM D7957/D7957-22, West Conshohocken, PA

Bakis, C.E., Al-Dulaijan, S.U., Nanni, A., Boothy, T.E., Al-Zahrani, M.M. (1998). Effect of Cyclic Loading on Bond Behavior of GFRP Rods Embedded in Concrete Beams, J. Compos. Tech. Res., 20 (1), 29-37.

Biondo, A.M., Guo, X. , Wu, R., Cao, L., Zhou, J., Tang, Q., Yu, T., Goplan, B., Hanna, T., Ivy, J., Wang, X. (2023). Smart textile embedded with distributed fiber optic sensors for railway bridge long term monitoring. Opt. Fiber Tech., 80, 103382. s

Biondo, A.M., Zhou, J., Guo, X., Wu, R., Tang, Q., Gandhi, H., Yu, T., Goplan, B., Hanna, T., Ivy, J., Wang, X. (2022). Pipeline structural health monitoring using distributed fiber optic sensing textile. Opt. Fiber Tech., 70, 102876.

Bremer, K., Weigand, F., Zheng, Y., Alwis, L.S., Helbig, R., Roth, B. (2017). Structural Health Monitoring Using Textile Reinforcement Structures with Integrated Optical Fiber Sensors. Sensors, 17 (345), 1-12.

CSA (Canadian Standards Association). (2022). Fibre reinforced polymer (FRP) reinforcement for concrete structures — Part 2: Specifications of CFRP strips. ISO 18319-2:2022. Toronto, Ontario, Canada: CSA.

Dagher, H.J., Bannon, D.J., Davids, W.G., Lopez-Anido, R.A., Nagy, E., Goslin, K. (2012). Bending behavior of concrete-filled tubular FRP arches for bridge structures, Const. Build. Mat., 37, 432–439.

Davids, W.G., Diba, A., Dagher, H.J., Guzzi, D., Schanck, A.P. (2022). Development, assessment and implementation of a novel FRP composite girder bridge. Const. Build. Mat., 340, 127818.

Davids, W.G., Guzzi, D., Schanck A.P. (2022). Development and Experimental Assessment of Friction-Type Shear Connectors for FRP Bridge Girders with Composite Concrete Decks. Materials, 15, 3014.

Hughes-Riley, T., Dias, T., Cork, C. (2018). A Historical Review of the Development of Electronic Textiles. Fibers, 6 (34), 1-15.

Gutierrez, E., Mieres, P.S., Calvo, J.M. (2008). Structural testing of a vehicular carbon fiber bridge: Quasi-static and short-term behavior, J. Bridge Eng., 13 (3), 271–281.

Karbhari, V.M., Seible, F., Burgueno, R., Davol, A., Wernli, M., Zhao, L. (2000). Structural characterization of fiber-reinforced composite short- and medium-span bridge systems, Appl. Comp. Mat., 7, 151–182.

Mieres, J., Calvo, I., Pineda, L., Botello, F., Gomez, M., Primi, S., Bonilla, J. (2007). First bridge constructed of carbon fibre reinforced polymers in Spain, Patras, Greece, 596–597.

Nawaz, W., M. Elchalakani, A. Karrech, S. Yehia, B. Yang, O. Youssf. (2022). Flexural behavior of all lightweight reinforced concrete beams externally strengthened with CFRP sheets. Constr. Build. Mater., 327, 126966-1-22.

OSHA (Occupational Safety and Health Administration). (2006). Respiratory protection – Personal Protective Equipment. Occupational Safety and Health Standards, 1910 Suboart I. 29 CFR 1910.134. US Department of Labor. Washington DC.

Ozbakkaloglu, T. (2012). Concrete-filled FRP tubes: Manufactire and testing of new forms for improved performance. J. Compos. Constr., 17 (2), 280-291.

Ozbakkaloglu, T. (2013). Compressive behavior of concrete-filled FRP tube columns: Assessment of critical column parameter. Eng. Struct., 51, 188-199.

Yan, Y., Lan, S., Jiang, Q. (2019). A Review on Concrete Structures Strengthened with CFRP Sheets Bonded with Organic and Inorganic Cementation Materials. Adv. Civil Eng. Mater., 8 (1), 1-8.

Seyam, A.M., Hamouda, T. (2013). Smart textiles: Evaluation of optical fibers as embedded sensors for structure health monitoring of fiber reinforced composites. J. Text. Inst., 104, 892–899.

Siwowski, T., Rajchel, M., Kaleta, D., Własak, L. (2017). The first Polish road bridge made of FRP composites, Struct. Eng. Int., 27 (2), 308–314.

Zhou, G., Sim, L.M. (2002). Damage detection and assessment in fiber-reinforced composite structures with embedded fiber optic sensors-review. Smart Mater. Struct., 11, 925–939.

Ziehl, P.H., Engelhardt, M.D., Fowler, T.J., Ulloa, F.V., Medlock, R.D., Schell, E. (2009). Design and field evaluation of hybrid FRP/reinforced concrete superstructure system, J. Bridge Eng., 14 (5), 309–318.

