The Use of Sensors for Safety Inspection and Evaluation of Bridges with FRP Composites

Topic: HIBS10-FRP-001

Principal Technical Point of Contact:

Dr. Dayakar Penumadu,
Fred N. Peebles Professor and JIAM Chair of Excellence, Civil and Environmental Engineering,
University of Tennessee Knoxville
325 Tickle Building, 851 Neyland Drive
Knoxville, TN 37996
Phone: 865-335-5980
E-mail: dpenumad@utk.edu

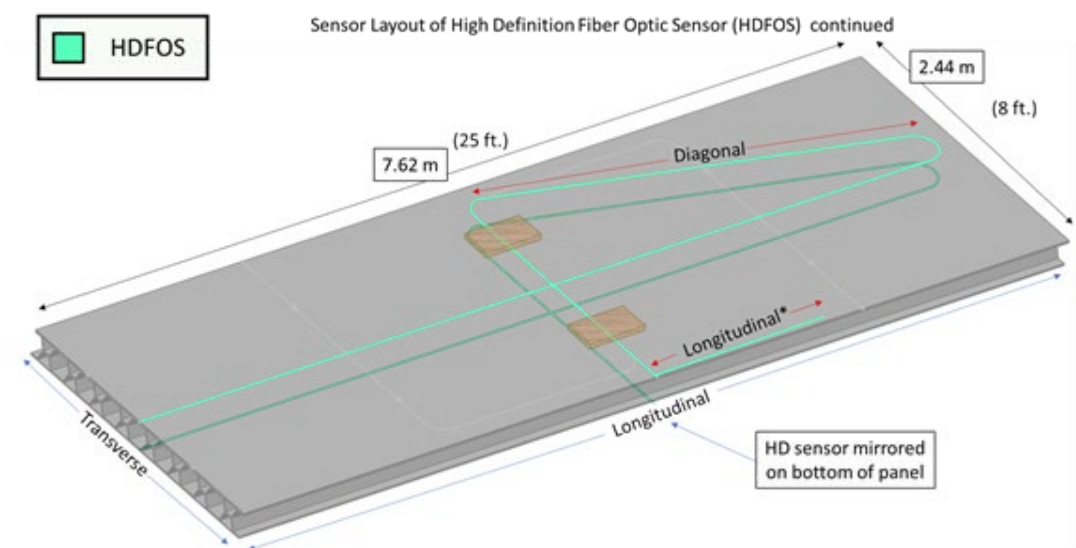
Contractual Point of Contact:

Heather Castleberry,
Chief Finance Officer,
IACMI - The Composites Institute managed by Collaborative Composite Solutions Corporation,
2360 Cherahala Boulevard
Knoxville, TN 37932
Phone: 865.946.1589
E-mail: hcastleberry@iacmi.org

Secondary Offeror Organizations (Project Partners):

Composites Applications Group, 10607 Lee Highway, McDonald, TN 37353
Luna, 301 1st Street, SW, Suite 200, Roanoke, VA 24011
Regulatory Resources LLC, 1018 Roanoke Drive, Westfield, IN, 46074
Structural Composites, 360 East Drive, W. Melbourne, FL 32904

Confirmation of SAM.gov registration: Collaborative Composite Solutions Corp is registered.
Date of Submittal: February 1, 2021
Proprietary Data Restrictions: None



Technical Approach

Background

Objective Statement: Fiber reinforced polymer (FRP) bridge decks with integrated continuous fiber optic sensors and a state-of-the-art wireless structural health monitoring system is proposed for the inspection and monitoring of FRP structures. These smart bridge decks are light weight, durable, easy to install, repairable, and lower cost when considering its life cycle analysis. Proposed project leverages a composite bridge deck demonstration project ongoing in Tennessee by the Institute for Advance Manufacturing Composites and Innovation (IACMI), USA national composite institute based in Knoxville, TN.

Description of Need: Between 1996 to 2004 it has been reported that a total of 83 bridges with FRP decks have been built in the United States[1], and the number of such bridges is continuously growing as bridge engineers become comfortable with the material and its performance. A lack of standardization in materials (resin, reinforcement, manufacturing process, analysis approach, design allowables, joining methods, sensitivity of field conditions during joining especially considering a given type of adhesives etc.) has been a challenge to civil engineers who are accustomed to standard shapes, sizes, and material properties. Correspondingly FRP decks have resulted in unique problems and maintenance issues associated with each type, thereby complicating the upkeep of these decks. Another major roadblock is a lack of course work in composite material design for civil and structural engineering majors. Having an automated and intelligent inspection and repair strategies will only significantly improve the potential use of FRP materials in bridge engineering and related infrastructure projects.

Technology Assessment: Inspection and damage detection methods used for FRP bridge decks involve visual inspection, tap test, thermal, acoustic, ultrasonic, x-ray imaging, and other techniques. Some of these are relatively low cost and reliable (for example tap test and visual inspection), but more sophisticated methods can prove to be highly specialized and expensive and for sandwich construction with foam core materials very difficult to implement considering wide variation of the manufacturing materials and methods. Damage types typically observed for these decs are cracks, holes, impact damage, abrasion or tearing, delamination, creep/stress rupture, fatigue damage, moisture ingress/absorption, UV or other weather-related damage, and other expected conditions in roadways (fire, heat, attachment to guard rails, freeze-thaw, etc.).

Development Framework: FHWA's Recording and Coding Guide for the Structures Inventory and Appraisal of the Nation's Bridges provides the uniform scale for condition rating from Failure (0) to Excellent (9) and NCHRP Project 10-64 report identifies them for FRP Decks which will serve as a starting basis. In addition, condition of deck joints and wear surface need to be considered along with curbs and sidewalks. One of the major challenges FRP decks is that research associated with damage estimation, damage accumulation, and remaining life prediction is currently incomplete. FRP bridge deck cross section between the top and bottom surfaces or face sheets is not visible for visual inspection and easily implementable tests such as tap test can detect damage such as delaminations or disbonds limited to areas close to the top and bottom surfaces of the deck. The adhesive joint between deck and beams and covered up regions of deck joint also lead to challenges with traditional bridge inspection strategies. We propose here integration of distributed fiber optic sensors during deck manufacturing (easy to accomplish for most currently composite manufacturing techniques) and the sensor becomes part of the deck and serves as thousands of strain gages located in the regions of interest using one or two fiber optic sensors only. Integrating fiber optic sensors, and wireless sensing of environmental variables including temperature, relative humidity, dynamic response of bridge deck with integrated multiaxial accelerometers will provide on demand data for the demonstration of durability, mobilized strains/stresses, and assurance of multi-material joining performance with support beams to accommodate both mechanical and thermal load transfer. Integrated high resolution wireless imaging cameras also provide necessary supplementary data valuable for visual inspection-based data analysis.

Scope of Work

Task 1 On-demand fiber optic sensing and wireless based environmental sensing: Morgan County is a rural community in Tennessee Congressional District 3 and is affected by the limited funds to repair its aging bridge inventory. The team of Structural Composites, Composite Applications Group, McKinney Excavating, University of Tennessee Knoxville (UTK), and IACMI The Composites Institute proposed to replace an aging 16-foot-long bridge and increase its width to 26 ft. In this demonstration project, a Morgan county concrete bridge deck system will be replaced with a fiber reinforced composite deck to be commercialized by Composites Application Group (CAG). We plan to leverage this demonstration FRP deck project to be used as a test bed for the proposed FHWA project on exploring novel strategies described above for bridge inspection. Monitoring of mobilized strains at various locations in the bridge decks will be done using multiple sensors and using two optical sensing interrogator instruments acquired from Luna Innovations, Inc available through Dr. Penumadu's labs.

The first instrument consists of Fiber Bragg Grating sensors (FBG) and a commercial high-speed measurement optical sensing interrogator (Hyperion si155) that will measure the dynamic and absolute strain measurements along the top of the deck panels. The second instrument is a commercial multichannel Optical Distributed Sensor Interrogator (ODiSI 6100) unit and High Definition Fiber Optic Sensors (HD-FOS), a lightweight fiber optic cable affording high spatial resolution as low as 0.65 mm, with thousands of sensor points, that will be utilized for strain measurements along the top and bottom of the deck panels with detailed relationship on mobilized loading and material response at various section of the composite bridge deck. Approximately 13.6 m of a 20 m HD-FOS, polyimide coated glass fiber, and 155 microns in outer diameter, will be bonded on each side of deck panels for a total of four sensors in the desired configuration based on expected high and low regions of strains. Similarly, approximately 12.2 m of a 50 m FBG will be bonded on the top of each panel for a total of two sensors. The unbonded or unsecured free length of sections of the HD-FOS (6.4 m) and FBG (37.8 m) will be carefully coiled into an enclosure box shown in Figure 1c. The HD-FOS and FBG will be bonded to the deck panels using an epoxy resin (Micro-Measurements, M-bond AE-10) along the segments of interest where the resin is cured for approximately 24 hours. The enclosure box will be positioned on one side of the bridge deck and will connect to remote modules. The remote modules are connected to the interrogators positioned in the bed of a truck vehicle to monitor the strain measurements of the deck panels. Relative humidity, temperatures at multiple locations on the deck, central support deflection, in-plane and out-of-plane accelerations will be monitored remotely and in wireless mode through cloud-based computing. The strain and temperature data will be utilized to obtain much needed thermal expansion and related metrics for joint design and durability of the material system.

Associated milestone is the demonstration of mobilized strains and health of bridge deck, joining assembly meeting the design expectations safely. This task metric will be to successfully evaluate adequacy of design and explore further optimization for cost reduction. Another important metric is to demonstrate the use of integrated fiber optic sensing and coupled wireless modules as a valid method for bridge inspection use and is identified to be of high priority for FHWA.

Task 2 Collaborate with and Integrate DOT bridge inspection experts: Tennessee Department of Transportation Bridge Inspection and Repair group led by Structures Director Mr. Ted Kniazewycz is responsible for the design and plans preparation of bridge repair projects on state-maintained bridges. The project team will collaborate closely to integrate TDOT bridge inspection experience to be captured in the proposed strategy so the sensor based data fusion with experience from traditional deck materials inspection strategies will be closely connected throughout the project duration.

Regulatory Resources LLC, a team member, facilities the DOT Advisory Board. The DOT Advisory Board will be a great resource to help the team understand the needs of the infrastructure.

Task 3 Write guide for use of sensors for safety Inspection and evaluation of bridges with FRP composites and repair strategies: IACMI will take the lead on developing a guide that explain the different sensors and how they can be used to monitor the health of bridge components made from FRP Composites. This guide would be a supplemental to the National Bridge Inspection Standard. Collaborative work with ACMA[2] will be targeted to provide practical strategies for composite repair.

Task 4 Web based interface for dissemination and data visualization and education: The project related data will be maintained on a web page and pertinent on-demand data will be stored on cloud resources for seamless access. Identifying essential data required for storage and long-term durability assessments will need to be developed as a part of this task. Using results of Tasks 1-3, build web based educational module to introduce bridge engineers and inspectors to unique aspect of FRP bridge deck elements and systems.

Task 5 Periodic project updates with FHWA program monitor(s) and related DOT officials

Expected Outcomes and Impacts

Three major outcomes of the project are knowledge, guidance, and education. The gathering of data on the several bridges with sensors installed will help the team understand what information is critical to monitoring the health of a FRP bridge deck. Working closely with the state DOTs will give the team insight into what is required. All this data will be captured into a detailed guide on the use of sensors to monitor the health of a FRP bridge. The website will be a great tool to educate the civil engineering community to the benefits of sensors and FRP composites.

Patented or proprietary items:

U.S. patent application number 16/314470 SMART JOINT FOR SIMILAR AND DISSIMILAR MATERIALS INCLUDING POLYMERS, FIBER REINFORCED COMPOSITES, METALS, CONCRETE, WOOD BASED PRODUCTS, AND OTHER STRUCTURAL MATERIALS. The applicant listed for this patent is University of Tennessee Research Foundation. Invention is credited to Dayakar Penumadu. This technology will be used to evaluate and inspect adhesive and hybrid (adhesive and bolted) joints.

Quad Chart

A Quad chart summarizing the project concept and cost is included on page 6 of this document.

Qualifications

Project Team

IACMI – The Composites Institute, a 130+ member Manufacturing USA Institute managed by Knoxville TN 501(c)3 company Collaborative Composites Solutions. IACMI and its members collaborate on TRL 4 – 7 R&D to advance composites manufacturing technologies to deployment. IACMI has more than 50 projects, collectively budgeted > $200M with individual project budgets from $100k - $15M, and over 90 members participating in projects. Major emphases include infrastructure, wind, vehicles, gas storage, simulation, supply chain development, and commercializing low-cost, not-yet-commercial carbon fibers. Other major areas are training, education, and work force development. **Key personnel**: Erin Brophy, Program Director, 15 years contract management; Heather Castleberry, Chief Finance Officer 20 years accounting experience.

The **University of Tennessee Knoxville** has state of the art multi-scale composites prototyping and materials characterization capabilities. **Key personnel**: Dayakar Penumadu, Ph.D., Endowed Professor and leader in UT's Joint Institute for Advanced Materials, is a recognized expert in a wide range of fiber and composites characterization and manufacturing methods and relating process-property relationships. He also offers a distance education-based class on mechanics of fiber reinforced composites and design.

Composite Applications Group (CAG) connects OEM manufacturers of products to technology companies within the composites industry. CAG is a consortium of companies that provides composite solutions for OEM's actively interested in replacing traditional materials with composites and other advanced materials. There is a lot of complexity in the supply chain. CAG helps those OEM's chart a path forward through collaboration with CAG technology members which represent the whole supply chain. Recently CAG formed and led a team to build and install the first FRP bridge deck in rural Tennessee. CAG harnesses the power of creativity and collaboration for stronger profitable success for the entire consortium. **Key personnel**: John Unser, VP Program/Project Management. a 32-year veteran of the composite industry. Peter Hedger, VP Business Development, 25 years composite industry

As the founder of **Regulatory Resources LLC**, Richard Krolewski draws on nearly two decades of interaction with Departments of Transportation, federal agencies, and municipalities, where he served as a liaison between the regulatory community and the construction industry. As the founder of Regulatory Resources LLC and an appointed representative of the U.S. DOT, he coordinates the DOT Advisory Board, a group of DOT officials seeking to advance the transfer of data for enhanced quality assurance on DOT projects.

Luna Innovations Incorporated (www.lunainc.com) is a leader in optical technology, committed to serving its customers with unique capabilities in high-performance, fiber-optic-based sensing, measurement, testing and control products for the aerospace, transportation, infrastructure, security, process control, communications, silicon photonics, defense, and automotive industries, among others. Luna is organized into two business segments, which work closely together to turn ideas into products: Lightwave and Luna Labs. Enabling the future with fiber, Luna's business model is designed to accelerate the process of bringing new and innovative technologies to market. Luna's fiber optic sensing solutions include sensors for a variety of measurements critical for an effective structural health monitoring (SHM) system. **Key personnel**: Matthew Davis, R&D Director 17 years sensor experience

Experience

The Morgan County Bridge Project was broken down into five tasks: design, construction, installation, monitoring/testing, Life Cycle Cost Analysis, and promotion. The bridge deck was designed and fabricated by Structural Composites. The support structure under the bridge deck was designed by a local engineering firm and approved by Joe Miller, the Morgan County Superintendent of Roads. The span was increased to 16 feet and the width was increased to 25 ft. The bridge deck was built off site under the direction of Structural Composites. Materials for the bridge deck will be donated by Structural Composites, Interplastic, Acra-lock, Superior, Luna, and METYX. UTK imbedded sensors into the bridge deck during fabrication. Site preparation and substructure/deck installation was performed by McKinney Excavating, Inc. Once installed, UTK performed baseline testing. IACMI monitored the progress of the bridge program to support the development of a Life Cycle Cost Analysis of the FRP Bridge Deck in comparison to traditional. TDOT was aware of the project and will also be monitoring the progress.

Schedule and Cost Estimate

	Month ->	1	2	3	4	5	6	7	8	9	10	11	12
	Weeks												
Task 1 On-demand fiber optic sensing and wireless based environmental sensing													
First bridge deck installed with monitoring capability	8												
Second bridge deck installled with monitoring cability	26												
Task 2 Collaborate with and Integrate DOT bridge inspection experts:													
Initial meeting with TDOT	12												
Document TDOT and other state DOT requirements	30												
Task 3 Write guide for use of sensors for safety Inspection and evaluation of bridges with FRP composites and repair strategies													
Draft guide ready for review	36												
Final guide submitted	52												
Task 4 Web based interface for dissemination and data visualization and education	52												
Initial website up and ready for review	16												
Website demonstation to FHWA and stat DOTs													
Task 5 Periodic project updates with FHWA program monitor(s) and related DOT officials	12												
	Month ->	1	2	3	4	5	6	7	8	9	10	11	12

Cost Estimate
$250,000 for a year program

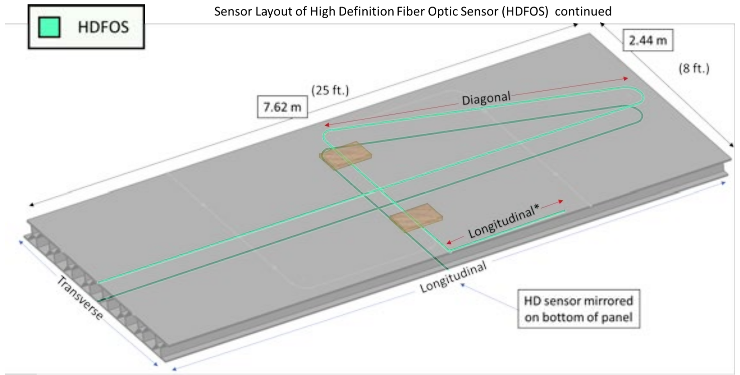
University of Tennessee Knoxville	60%
IACMI	10%
Composites Applications Group	14%
Luna Innovations	8%
Regulatory Resources LLC	8%

[1] National Academies of Sciences, Engineering, and Medicine 2006. Field Inspection of In-Service FRP Bridge Decks. Washington, DC: The National Academies Press. https://doi.org/10.17226/23284.

[2] Busel, John P., American Composites Manufacturing Association, 2017. Trends in Infrastructure. IACMI Members Meeting, Dayton, OH.

The Use of Sensors for Safety Inspection and Evaluation of Bridges with FRP Composites

Sensor Layout of High Definition Fiber Optic Sensor (HDFOS) continued



Bridge and/or Tunnel Impact

- Demonstrate the use of integrated fiber optic sensing and coupled wireless modules as a valid method for bridge inspection
- Guide on use of sensors to supplement to the National Bridge Inspection Standard.
- Tools to help educate civil engineering community about FRP Composites

FHWA Task Monitor: Tuonglinh Warren

Project Description

- Demonstration of sensors to monitor health of FRP composites bridges
- Develop guideline for inspectors when they have access to sensor data
- Implement web-based interface for dissemination and data visualization and education

Cost & Schedule

- $250,000 for a year program
- University of Tennessee Knoxville 60%
- IACMI 10%
- Composites Applications Group 14%
- Luna Innovations 8%
- Regulatory Resources LLC 8%

Project Partners: IACMI The Composite Institute, University of Tennessee Knoxville, Composite Applications Group, Luna Innovations, Regulatory Resources LLC,

U.S. Department of Transportation
Federal Highway Administration