Connecticut Permanent Long-Term Bridge Monitoring Network Volume 5: Wireless Monitoring of the Hung Span in a Large Truss Bridge – I-95 NB over the Thames River in New London (Bridge #3819)

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Disclaimer

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16. Abstract

This report describes the instrumentation and data acquisition for the center hung segment in the largest truss bridge in Connecticut, located on the interstate system. The monitoring system was developed as a joint effort between researchers at the University of Connecticut and a company manufacturing wireless sensor technology, and it is the first of its kind. The great lengths between sensors, along with the difficulty of running wires over the trusses, led to the decision to use wireless sensors. Access to the underside of the bridge is severely limited, requiring closing of a lane whenever researchers are on the bridge. Since wireless sensors require batteries for power, necessitating replacement of batteries on a regular basis, researchers proposed use of solar panels along with rechargeable batteries for use with the sensors. The initial system was developed and placed on the bridge and used to collect strains and accelerations. Using what was learned from the initial system, changes and upgrades were made to the equipment. This included sensor modifications, replacement of some of the solar panels and revisions to the monitoring techniques. This report shows what was learned from the initial phases for this first-of-its kind monitoring system.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Wireless Monitoring of the Hung Span in a Large Truss Bridge –

I-95 NB over the Thames River in New London (Bridge #3819)

INTRODUCTION

Researchers at the University of Connecticut and in the Connecticut Department of Transportation have been using field monitoring to explore the behavior of bridges during the past two and a half decades (Lauzon and DeWolf, 2003). This report is based on the research project that was developed to place long-term monitoring systems on a network of bridges in the state (DeWolf, Lauzon and Culmo, 2002; Olund and DeWolf, 2007; DeWolf, Cardini, Olund and D'Attilio, 2009). The first system was installed in 1999, and since then five other bridges have been added to the network. The bridges have been selected because they are important to the state's highway infrastructure and because they are typical of different bridge types. Each monitoring system has been tailored to the particular bridge, using a variety of sensors, and all data is collected remotely. As with many of our busier highways, it is not possible to close a bridge for monitoring, and thus all systems collect data from normal vehicular traffic. The goal of this research has been to use structural health monitoring to learn about how bridges behave over multi-year periods, to provide information to the Connecticut Department of Transportation on the behavior of the state's bridges, and to develop structural health monitoring techniques that can be used to show if there are major changes in bridges' structural integrity.

The current four-year phase in this long-term project has focused on installation and implementation of monitoring systems on two new bridges, substantial upgrading of the monitoring equipment, with addition of video collection, and development of techniques for long-term structural health monitoring. This is one of the new bridges that a monitoring system was installed on during the course of this current phase of the project.

This report involves the Gold Star Bridge (Inventory Number 3819). The bridge crosses the Thames River in the southern part of Connecticut. It carries the Interstate I-95 over the river that is used by submarines to access the nearby submarine base. The submarines pass under the central span, with its hung truss span. An aerial view of the bridge is shown in Figure 1. It is the larger bridge in the background; a rail road truss bridge is shown in the foreground with an open span. There are two separate bridges in this complex, one for the west direction in the back and one for the east direction, located between the back span and the railroad bridge. The monitored span crosses in the east direction, and it is the older of the two bridges on the interstate. An elevation of the bridge is shown in Figure 2. The monitored segment is in the center span, at the highest elevation in the photo.

Figure 1. Gold Star Bridge

Figure 2. Bridge Elevation

The monitored bridge was built in 1944. It carries five lanes of traffic, with break down lanes on each side. The overall bridge length is 5923 feet. The length of the monitored truss portion is 3745 feet. A photo taken in the superstructure, below the deck, is shown in Figure 3.

Figure 3. Bridge Superstructure

The span of interest has a 216 feet long central section that is supported by hangers at each end. The four original hangers at each corner are built-up square sections. A photo of the hanger is shown in Figure 4. Following collapse of the Mianus Bridge, back-up hanger systems were added to all Connecticut bridges with hangers. The back-up system used for each of the hangers in this bridge consists of 16 threaded rods, as shown in this Figure 4. The original hangers are pinned at each end. Figure 5 shows one of the pin caps at the hanger top.

Figure 4. Hanger

Figure 5. Pin Cap

OBJECTIVES AND SCOPE OF STUDY

The objective of this study was to design a wireless monitoring system, using solar panels to power the sensors, to collect both strains and accelerations. This involved a new approach in the larger monitoring project developed to put long-term monitoring systems on Connecticut bridges. The current research combines the expertise developed in the application of long-term bridge monitoring systems on Connecticut bridges, wireless sensor technology that had been in use, and solar panels to provide power for sensor excitation and transmission. The use of solar power for the sensors had not previously been used. This new approach provides another way to monitor a wide variety of bridges, without the installation length needed with wired systems or continued maintenance that was required for wireless sensors.

The hangers and adjacent members of this section were chosen for monitoring to evaluate the structural integrity of the hangers, on the assumption that if there were concerns on this bridge, this would be key to maintaining access to the submarine base. Also, the hanger sections are key fatigue details (Mehta 2001). Thus, the monitoring system was designed to demonstrate how this important hung span could be monitored.

The evaluation of the field data includes the development of computational techniques to explore the behavior of the hung span in the bridge and to provide a continuous picture of the performance, based on use of both strain gages and accelerometers. Of key importance is the ability to assure that the hangers are performing as designed.

INSTRUMENTATION AND DATA ACQUISITION

The monitoring system was designed to study the behavior at the hangers, involving both the hung span and the supporting span. Eight strain sensors and four accelerometers have been used in this demonstration system to show how long-term monitoring can be used to assure the integrity of the hangers. While there is a catwalk in the vicinity of the hanger connections, a field visit showed the difficulty in placing and running wires to the cabinet with the monitoring equipment. Additionally, using wires for each sensor does not readily allow for movement of sensors over time. Thus, wireless sensors were proposed.

At the time of design of the monitoring system, wireless technology was being used for short-term evaluations of bridge performance. The majority of the research in this area had been devoted to the development of the technology. A thorough review of the literature produced only one application that was related to what was proposed in this study. Galbreath, Townsend, Mundell, Hamel and Arms (2003) demonstrated the effectiveness of using a wireless monitoring system on a heavily trafficked steel girder composite deck bridge spanning the LaPlatte River in Shelburne, VT. The study was carried out by The University of Vermont in collaboration with MicroStrain Inc. The sensors were installed with magnetic mounts on the bottom flange of the central beam, near the bottom of the beam web. A total of eight strain sensors were applied. The data logging transceiver platform, located approximately 115 feet from the sensors, provided for eight channels of analog input with a low power 8-bit micro-controller that collects sensor data via an 8 channel, 12 bit successive approximation A/D converter. This data was stored locally to an onboard 2MB flash memory chip. At the user end there is a base station with the same telemetry hardware. The telemetry hardware was bi-directional, so that the base station could also send data to the remote nodes. Since the telemetry hardware is bi-directional, the user can configure the operational parameters of the node wirelessly and trigger data collection from the central monitoring platform.

The disadvantage of the wireless technology is the need to provide battery power at each sensor location. This requires changing batteries at specified intervals, eliminating part of the advantage of using wireless technology. Discussion of the possibility of using solar panels to recharge the batteries led to the joint development of a new system to combine the benefits of wireless sensors with the need for continuous use over long-time periods. The design criteria for the monitoring system were based on the following components:

- Eight wireless strain gages with magnetic mounts.
- Four wireless accelerometers with magnetic mounts, operating with a sleep timer with random wake-up. This would allow multiple periodic transmitters to operate on the same communications channel with a very low collision probability.
- Wireless web sensor network that allows for communication of the digital data to a single receiver system located at the monitoring box currently placed on the bridge at a maximum distance of 115 feet from the sensors.

The system is controlled by a laptop computer located on the bridge. The laptop provides for communication with each sensor, using a USB powered antenna for communication with the sensors. The system was manufactured and tested by MicroStrain in Vermont. Olund (2007) reviewed the design of the system, installation and start of data collection.

The original monitoring approach was based on using software that was uniquely coded so that it prompts each sensor to record for two minutes at the beginning of nearly every hour and to "sleep" between record periods. This reduced the amount of sensor energy needed, assuring that the batteries maintain sufficient power between recharging by the solar panels. Data from the sensors would be sent to the laptop on a daily basis. When this happens, the memory on the sensors is cleared to allow room for new data.

Unlike other monitoring systems in the project, the software was not configured to allow for triggered events, which then provide for the saving of data only for these events. The decision not to use triggered events was done to save power. This approach limits the data to a manageable and storable amount, and it provides consistent time intervals for recorded data. The laptop was equipped with software for remote access and control from the University of Connecticut main campus.

Individual sensors are contained in weatherproof boxes along with a 12V rechargeable battery. Figure 6 shows the inside of a sensor containment box. Included with the sensor is a small memory card for storing data until the sensor is prompted to transmit the data back to the laptop.

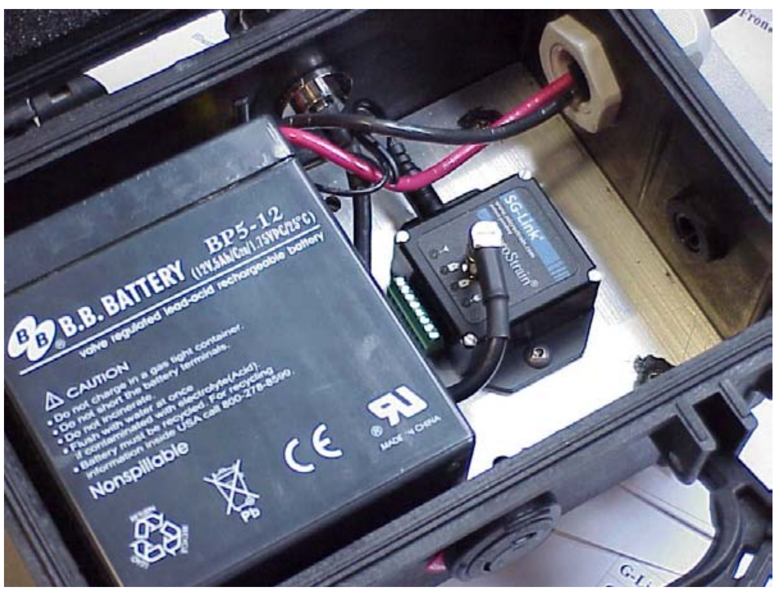

Figure 6. Typical Sensor Containment Box

Figure 7 shows two of the strain gages (on left) and one of the accelerometers (on right), attached near the bottom of one of the hangers. Each box has an antenna as shown. The wires connect the boxes to solar panels located near the boxes. Figure 8 shows a bank of five 10-inch by 15-inch solar panels, one for each sensor.

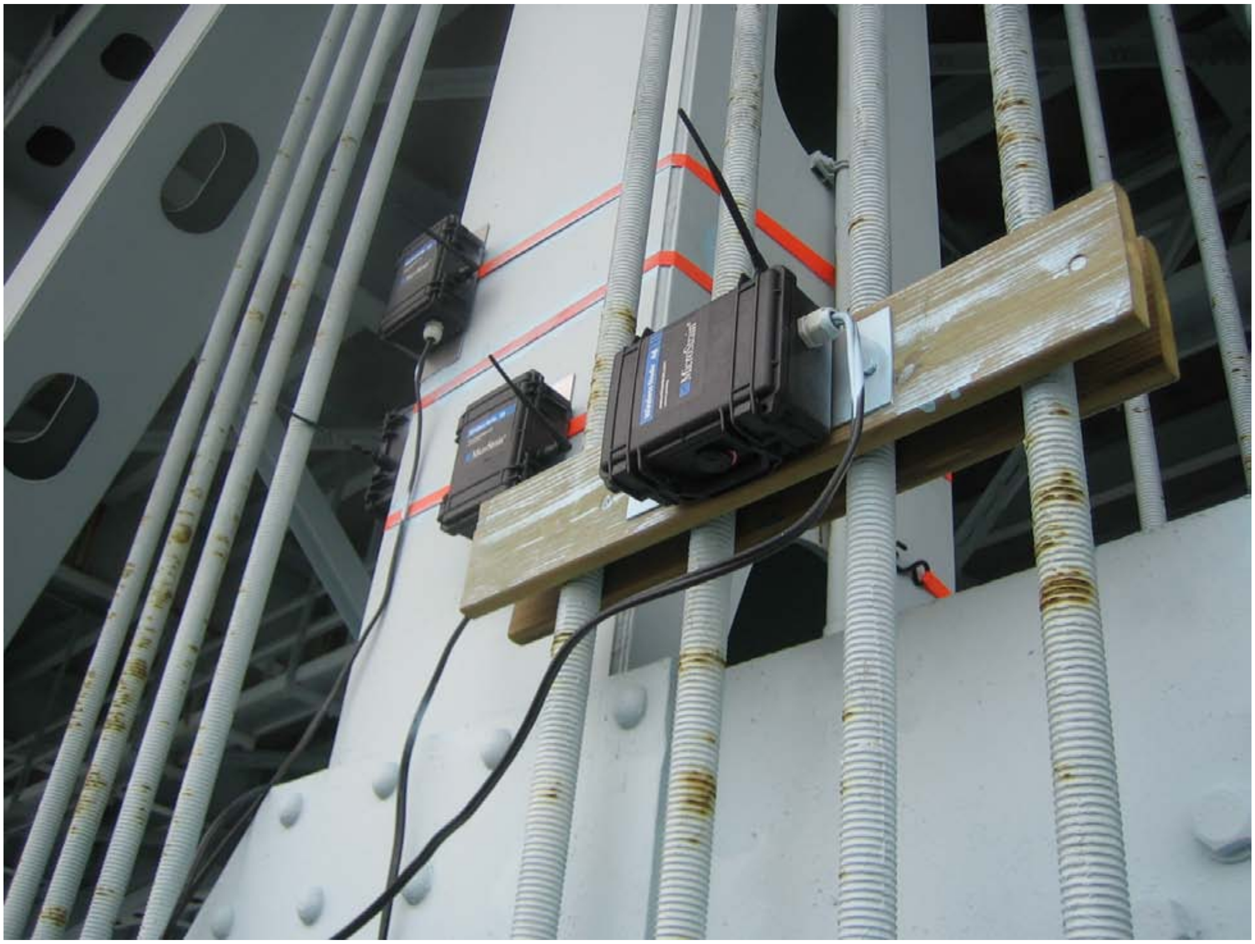

Figure 7. Strain Gages and Accelerometer

Figure 8. Solar Panels

The location of the sensors is shown in Figure 9.

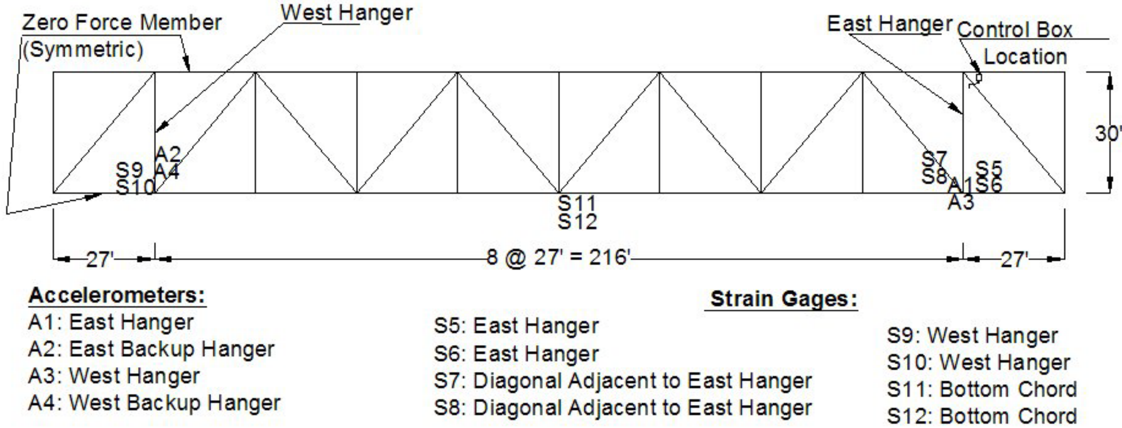

Figure 9. Sensor Placement

The accelerometers are located on separate sets of threaded rods, used as a back-up system for the hanger. The eight strain gages are placed to monitor the forces in the hangers and the force in the bottom chords at the center of the hung truss span. Two strain gages are used on each of the monitored members. Gages are placed in the axially loaded direction, on adjacent faces of the member, and on opposite corners. Figure 10 shows the location of the strain gages on one of the hanger cross sections. This positioning of the gages provides for determination of both the hanger axial load and the bending stresses.

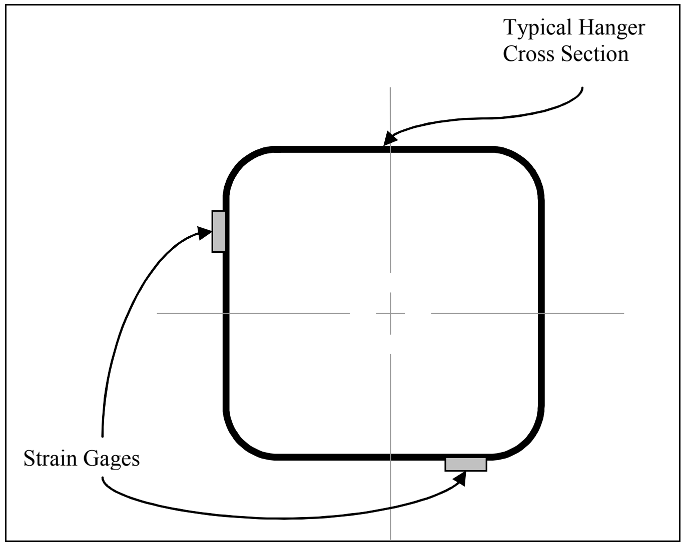

Figure 10. Typical Strain Gage Placement on Hanger

The system was tested at the University of Connecticut prior to installation on the bridge. It was installed on the bridge in November 2006. The first year was spent trouble shooting the system. Monitoring system issues included laptop failure, battery failure, faulty antennae, power outages at the laptop, software miscoding, and miscellaneous hardware malfunctions, primarily related to the severity of the environment. The entire system was first fully operational October 2007. Unfortunately, this was followed by power problems on the bridge, and as a result, the laptop monitoring system was not functioning on a regular basis.

During the period between 2007 and 2010, there were only limited opportunities for data collection, primarily following visits to the bridge to reset the system. While reliable data was not available, much was learned about the monitoring system. This led to proposed modifications, as explained in the next section.

DESIGN OF NEW MONITORING SYSTEM

After much effort and discussion between researchers at the University of Connecticut and MicroStrain, it was determined that the lessons learned from the initial system should be used to upgrade the solar powered, wireless monitoring system. Problems to be addressed were: (1) reliability of transmission of data from the farthest nodes to the computer; (2) the reliability of the laptop used to communicate with the wireless sensors; and (3) the need to have the batteries and solar panels used in the system provide for continuous operation.

The following improvements are recommended:

- Elimination of the PC in favor of our new WSDA data acquisition box.
- Replacement of all 12 strain gage and accelerometer nodes with new MXRS nodes with extended range up to 1Km and time synchronized technology (all nodes will be sensing within +/-30 microseconds of one another).
- Replacement of the base station antenna with a more physically secure mount and more range.
- Improved attachment of the accelerometer nodes to the beams (currently they are in the Pelican boxes which are mounted by straps and there is a dampening effect to be concerned about).
- Change the data collection to use of the Internet using MicroStrain's SensorCloud portal and secure web browser access on a full-time basis, including automatic event alarms (like heavy vibration) to email, SMS and iPods.

CONCLUSIONS

This project was successful in developing a new monitoring system for the central hung span in the longest truss bridge in Connecticut. The system combined existing wireless sensor technology with solar panels so that it would not be necessary to routinely change batteries on this difficult to access bridge. Sensors were used to collect both strains and accelerations. The initial phases of this research have advanced the state-of-the art for using wireless sensors as a way to provide for long-term structural health monitoring.

For various reasons, including logistical and financial challenges associated with installing and troubleshooting a monitoring system on a bridge of this size, ConnDOT officials decided to not pursue the installation of the new system at this time. The lessons learned and documented in this practice-ready report will serve as a valuable research reference to practitioners and researchers moving forward.

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REFERENCES

DeWolf, J. T., Lauzon, R. G. and Culmo, M. P. (2002). “Monitoring Bridge Performance.” Structural Health Monitoring Journal, Vol. 1, No. 2, pp. 129-138.

DeWolf, J. T., Cardini, A. J., Olund, J. K. and D’Attilio, P. F. (2009). “Structural Health Monitoring of Three Bridges in Connecticut.” Annual Meeting of Transportation Research Board, Washington, D.C., 17 pages.

Galbreath, J. H., Townsend, C. P., Mundell, S. W., Hamel, M. J., Esser, B., Huston, D. and Arms, S. W. (2003). “Civil Structure Strain Monitoring with Power-Efficient, High-Speed Wireless Sensor Networks.” Structural Health Monitoring 2003 Conference, Palo Alto, CA, pp. 1215-1222.

Mehta, S. (2001). “Stress Spikes in Pin and Hanger System of Truss Bridge.” ASCE Journal of Bridge Engineering, Vol. 6. No. 2, pp. 103-109.

Olund, J. K. and DeWolf, J. T. (2007). “Passive Structural Health Monitoring of Connecticut’s Bridge Infrastructure.” Journal of Infrastructure Systems, American Society of Civil Engineers. Vol. 13, No. 4, pp.330-339.

Olund, J. K. (2007). “Structural Health Monitoring Applied to Connecticut’s Bridge Infrastructure.” Doctoral Dissertation, University of Connecticut, Storrs, CT.