4th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-4) 2009
22-24 July 2009, Zurich, Switzerland

Wireless Monitoring of a Multi-Span Bridge Superstructure for Structural Identification and Evaluation

Michael V. Gangone, Matthew J. Whelan, Kerop D. Janoyan

Clarkson University Department of Civil and Environmental Engineering
Potsdam, NY 13699 USA

ABSTRACT: Improved methods of condition assessment utilizing modern sensor technology is being sought to complement existing qualitative assessment protocols. Wireless sensor technology is becoming an attractive solution for bridge monitoring due to the relative ease of installation, reduced system and deployment costs and versatility for monitoring a wide range of structures. This paper focuses on the deployment of a Wireless Sensor System (WSS) developed at Clarkson University for structural monitoring and condition assessment purposes. The WSS is designed specifically for diagnostic bridge monitoring, providing independent conditioning for accelerometers, strain transducers, and temperature sensors in addition to high-rate wireless data transmission and is capable of supporting large-scale sensor arrays. A three span simply supported structure was monitored under ambient and forced loading conditions. A total of 90 wireless sensors, including accelerometers and strain transducers were used in the deployment. A wired system supplemented the field measurements by providing additional strain readings. Strain measurements provided capacity and demand characteristics of the structure in the form of neutral axis locations, load distribution, and end restraint from the bridge bearings. Modal characteristics of the structure, including natural frequencies and mode shapes, were derived from measured acceleration readings.

1.0 INTRODUCTION

As a significant portion of the aging network of highway bridges have met or exceeded their intended design lifetime and service limits, highway administrations are faced with the challenging task of allocating limited resources for replacement and rehabilitation of structures most critical for repair while managing the remaining end-of-life bridges without jeopardizing public safety. As demonstrated in the aftermath of recent bridge collapses over the past several decades, current schedule-based visual inspections fall short of ensuring a safe operational model for highway bridge management with bridge closures preceding imminent failure. The increase in demand on highway infrastructure has coincided with the aging of a substantial percentage of the in-service national bridge inventory creating a greater urgency for quantitatively determining both the capacity and capabilities of highway infrastructure. As with all mechanical systems, bridge components deteriorate over time due to the effects of weather and stress cycling. This deterioration results in a reduction in the intended performance that can ultimately lead to structural failure. As of 2007, an estimated 26 percent of the nations 600,000 bridges are currently classified as structurally deficient or functionally obsolete by the Federal Highway Administration (FHWA) (FHWA, 2007). This suggests that the need for inspections of bridges is necessary and methods to repair and locate the damage are also important.

Local, visual evaluations are often flawed in that they may not always accurately reflect the true performance state of bridge components nor the global condition of the entire bridge. Subjectivity on the part of the inspection team is a critical and unaddressed obstacle to the effectiveness of the bridge inspection program. Additionally, time and access to the structure are generally cited as issues routinely encountered during the evaluation of bridges. Structural components are not always easily accessible to the inspector and, therefore, cannot be assessed nor contribute towards the overall rating of the structure. Many times these elements, whether primary or secondary, are critical to the overall performance, load capacity, and structural response. With time being of the essence, the level of detail and proper attention given to each and every element is often overlooked and inspectors are prone to assuming the condition of most members is average. In 2001, the Federal Highway Administration (FHWA) conducted a study which found that 56 percent of medium to short span bridges given an average condition rating were improperly assessed (Aktan et al., 2001). The introduction of quantitative, measurement-based evaluation methods into the existing inspection framework will undoubtedly overcome the subjectivity and physical constraints limiting the effectiveness of the bridge inspection program.

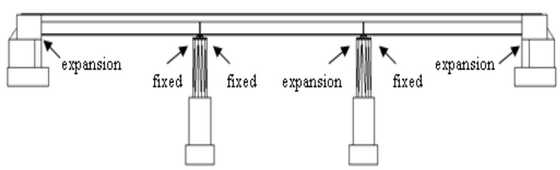
Acceleration and strain measuring devices are two of the more common sensor types deployed for typical bridge monitoring. Currently, many state transportation agencies including the New York State Department of Transportation (NYSDOT) utilize load testing with strain transducers to measure the performance and capacity of a bridge (Hag-Elsafi, 2006). Load distribution, dynamic impact factors, end fixity levels and composite action between the deck and girders are evaluated to quantify the structural stiffness as well as load transfer and redundancy of the system and can either verify a design method or indicate the level of service life remaining in the structure. Accelerometers capture the dynamic response of the structure under ambient and forced vibrations allowing for, among other things, the determination of the modal properties (mode shapes, damping ratios and natural frequencies). Whether utilizing global or local monitoring methodologies, providing a greater number of sensors and sensor types (i.e. accelerometers, strain transducers, thermocouples etc.) generally results in an improved overall representation of the structural performance.

Researchers are working to develop methods of structural monitoring to allow the complete and accurate assessment of structural performance in a non-destructive manner. DeWolf et al. (2006) are currently monitoring a series of bridges within the state of Connecticut, including a steel truss bridge using wireless strain gages and accelerometers. Wireless sensors were chosen due to the long span lengths and difficulty of instrumenting a cabled system over the long span lengths. Lynch et al. (2006) deployed a wireless system on the Geumdang Bridge in South Korea**.** Test vehicles provided an input loading to the concrete box girder bridge where acceleration measurements supply the modal characteristics of the structure. Whelan et al. (2008a) deployed 60 channels of wireless acceleration measurements over two networks of a 360 foot 3 span continuous bridge superstructure. The measurements were sampled in real time and served to obtain the various modal characteristics of the structure including natural frequencies and mode shapes. Gangone et al. (2008) deployed 11 channels of strain data on an integral abutment bridge obtaining various load testing parameters. Bridge Diagnostic Incorporated (BDI) (2008) has recently developed a wireless strain based system for bridge monitoring. While various research and commercial systems have been developed and implemented, methodologies of detecting and locating damage are of the utmost important to any health monitoring system. This paper focuses on the deployment of a Wireless Sensor System (WSS) on a three span simply supported bridge in Waddington, NY. Modal and strain based characteristics of the superstructure were acquired through measurements taken from 99 different sensors over a two day period. The results provide a quantitative assessment into the structural performance of the bridge.

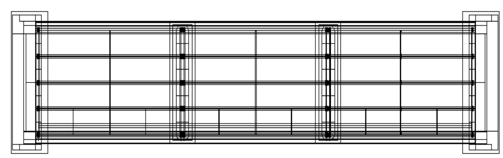
2.0 WIRELESS SENSOR NETWORK BASED BRIDGE MONITORING

The Wireless Sensor System (WSS) developed within the Laboratory for Intelligent Infrastructure and Transportation Technologies (LIITT) at Clarkson University was designed as a universal platform for high-rate, large-scale monitoring of the structural response (figure 1). The sensor network is composed of an array of distributed sensing nodes that interface with sensors (i.e. accelerometers, strain transducers, temperature sensors), condition analog signals, then convert them to digital format, and transmit the readings to a base coordinator. The base coordinator features the same wireless transceiver hardware as the remote nodes; however, its function is to control bi-directional wireless communications between the host computer and the distributed sensing units. The base coordinator is connected to the host computer across a Universal Serial Bus (USB) connection as a virtual COM device. This physical hardware interface is advantageous as it enables either network control from a CPU local to the measurement site or remote access across an internet connection through TCP/IP protocol using a network-enabled USB hub. The primary hardware issues addressed in design of the wireless sensing units were appropriate signal conditioning for the range of responses typical for the spectrum of highway bridge designs and span-lengths, minimized power consumption for battery resource conservation, and high-throughput network communications. A total of thirty wireless units, consisting of an accelerometer, strain transducer and custom conditioning system were developed and used in the monitoring. For more information on the developed wireless system see Whelan and Janoyan (2008) and Whelan et al. (2008b).

Figure 1: Wireless Sensor Solution (WSS) node with accelerometer and strain transducer.



(a) Elevation



(b) Plan

(c) Photograph

Figure 2. Test Structure: RT345 Bridge over Big Sucker Brook.

3.0 WIRELESS SENSOR FIELD DEPLOYMENT

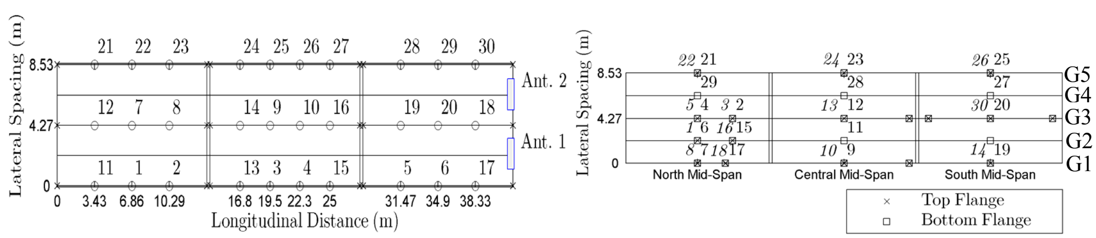
3.1 Test structure

The highway bridge investigated consists of a 19.1 cm (7.5 in) thick reinforced concrete slab supported by three interior W33x152 and two W33x131 exterior steel girders over each span (figure 2). The bridge is a two-lane structure consisting of three 13.7 m (45 ft) simply supported spans carrying a total span of 41.7 m (137 ft) at an elevation of approximately 1.2 m (4 ft) from the waterline. The girders have a center-to-center spacing of 2.1 m (7 ft) and are supported by fixed and rocker steel bearings. End and mid-span intermediate diaphragms are constructed of C15x33.9 sections that are bolted to transverse plates welded to the girders. Prior to the scheduled closure for replacement, the structure serviced New York State Route 345 over Big Sucker Brook in the town of Waddington. Constructed in 1957, the bridge maintained a sufficiency rating of 76.5%, an operational rating of 44.5 metric tons, and an average daily traffic estimate of 964 vehicles. Testing was completed over a three day period where day one consisted of modal testing through acceleration measurements, and day two a load test using 2-H trucks each weighing 23.97 tons for recording strain measurements.

3.2 Instrumentation

The bridge was instrumented at thirty locations over the three spans with dual-axis accelerometers for a total of sixty vibration sensors (figure 3a). The use of a large number of stationary accelerometers enables simultaneous collection of vibration time histories across the structure. This is advantageous to using a roving system with reference accelerometers as it ensures consistent temperature, ambient vibration, and traffic loading. Furthermore, a stationary array would be necessary for permanent installation, so the deployment validates the ability of the network to deliver the required bandwidth for a long-term network infrastructure. Sampling durations of three minutes were collected through real-time transmission of the processed raw ADC conversions.

On the subsequent day of testing, thirty strain transducers were installed across the structure for interfacing with the wireless sensor nodes with an additional nine wired transducers monitoring bearing restraint of selected girders in the south and center spans and the bottom flange at mid-span of girder 2 (G2) (figure 3b). The Bridge Diagnostics, Inc (BDI) transducers are Wheatstone full bridge resistive sensors housed in a durable, reusable transducer package that is mounted to the structure using bolted tabs. The instrumentation layout devised is typical of experimental load ratings (Hag-Elsafi, 2006). Placement of gauges at the top and bottom flange of a girder at the same longitudinal location facilitates determination of the neutral axis of bending. Gauges at the mid-span of each girder enable distribution factors to be recorded for each load case, which indicate load shedding paths. As in the case of vibration monitoring, the sensors were sampled at 128 Hz and transmitted in real-time to the network coordinator over test durations of three minutes.



(a) Accelerometer Locations (b) Strain Transducer Locations

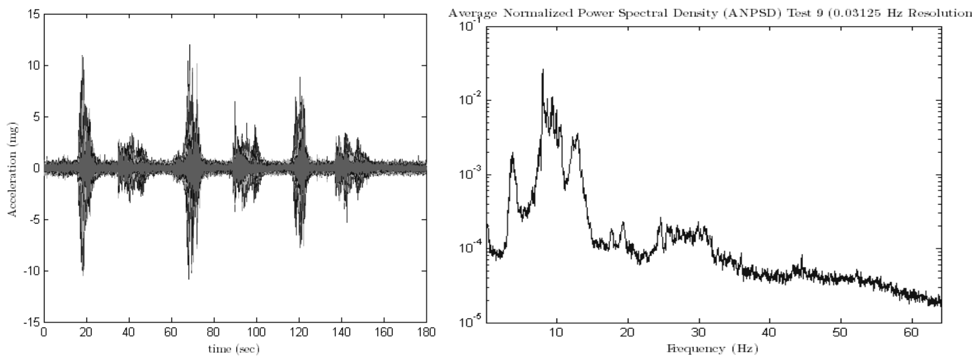
Figure 3. Instrumentation layout for testing performed at the RT345 Bridge site.

4.0 ANALYSIS OF RESULTS

4.1 Operational Modal Analysis

Two simultaneously operating wireless sensor networks were deployed on the RT345 bridge to enable the collection of vibration time histories from sixty accelerometers. Since the bridge was closed to normal vehicular traffic, ambient traffic excitation was provided by means of a large truck that started from rest just ahead of one abutment, travelled across the bridge at approximately 10-15 mph, and then returned in reverse. During the operational modal analysis, the truck made passes in both lanes as well as down the centerline of the bridge. A typical acceleration time history reveals peak accelerations generally in the range of 10-15mg (figure

4a). The relatively sparse placement of sensors across the entire structure limits the effectiveness of the modal analysis to primarily the lower order bending modes, though there are a significant number of modes that can be reconstructed from such an instrumentation layout. The average normalized power spectral density revealed that the first order natural frequencies of the spans were generally in the range of 8Hz to 13 Hz (figure 4b). Mode shapes were estimated from application of stochastic subspace identification (figure 5). The mode shapes and spectral content reveal that the spans are generally similar in response, though the natural frequencies vary with span. This is likely due to pre-existing deterioration, temperature effects, or end-fixity/bearing discrepancies, as the spans share a common design and length.



(a) (b)

Figure 4. (a) Typical vertical acceleration time history from truck passes, (b) Spectral content from distributed vibration measurements.

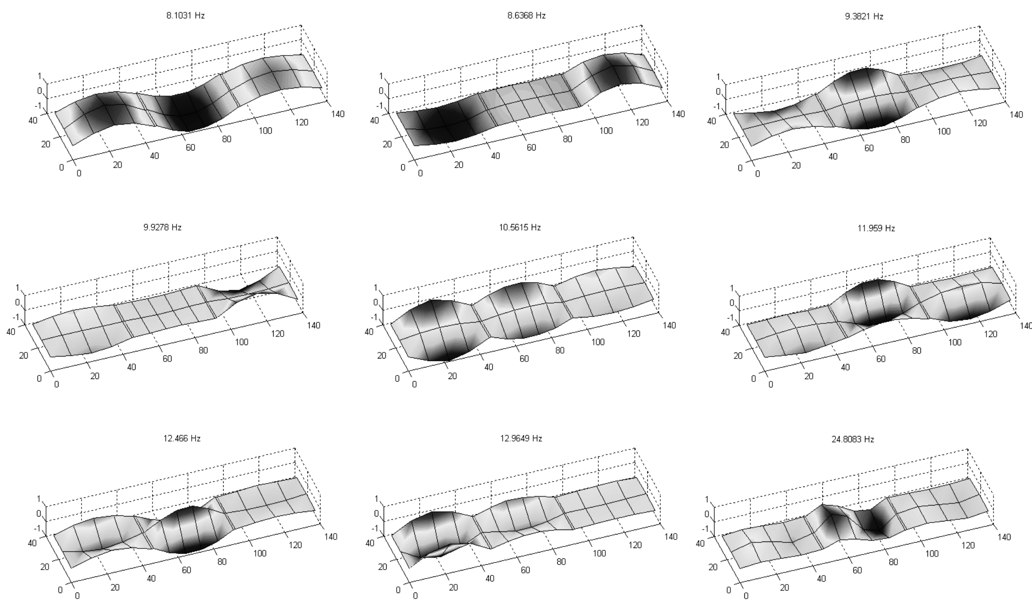
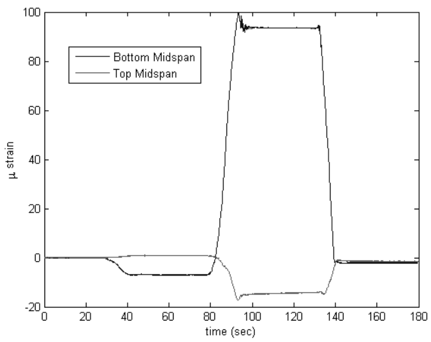


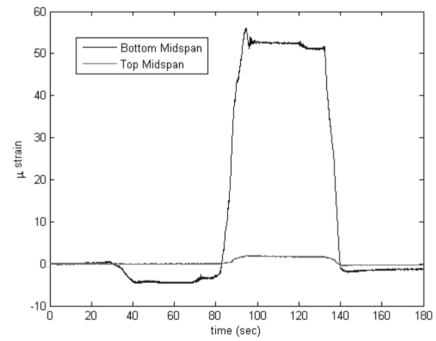
Figure 5. Lower Order Mode Shapes.

4.2 Strain Based Analysis

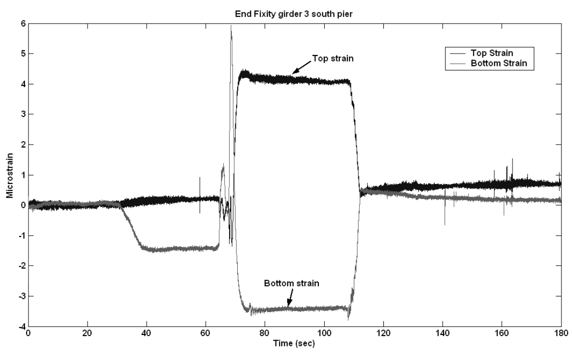
Load testing protocol, similar to that employed by NYSDOT (Hag-Elsafi, 2006) for a concrete deck on steel girder design, was completed on the Route 345 Bridge in Waddington. A total of 39 BDI strain transducers were deployed at the mid-span, near the supports and in selected deteriorated sections within the north span. Two sensors directly next to each other (i.e. 2 and 3 or 20 and 30) as shown in figure 3(b) indicate monitoring on the top and bottom flanges for calculating the neutral axis location. A typical strain response at the mid-span of an interior and exterior girder of the center span as well as at a bearing on the south pier of the center span is illustrated in Figure 6. Twenty-three wireless and one wired sensor at the mid-span (bottom flange of G2 on the south span) were utilized for determining various section properties and demand parameters within the structure. A total of 7 static (i.e. stationary) load tests were conducted using a combination of two H trucks (weighing 23.97 tons each) in three separate loading lanes.



(a)



(b)



(c)

Figure 6. Typical Strain Response measured (a) at an interior girder, (b) at an exterior girder, (c) at a bearing.

4.2.1 Neutral axis locations

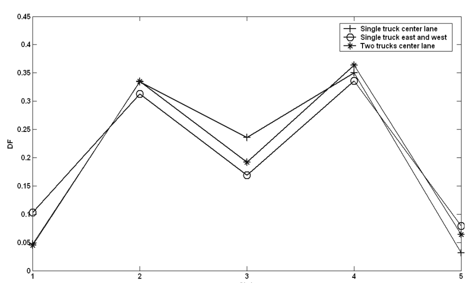
Of particular interest were characteristics of the structure related to the level of capacity and demand. Neutral axis (NA) locations and transverse load distribution factors (DF) were established within each of the three different spans. The neutral axis locations were computed from strain measurements at the top and bottom flanges of the girder assuming a linear strain profile along the depth of the section. Table 1 highlights the average neutral axis value taken from the 7 tests for each girder. It is noted that in the north span, girders 2 and 3 did not display relevant values and therefore were discarded from the analysis and reported as N/A (not available). This was also the case for selected tests completed within the remaining two spans whose values were discarded in the averaging process. Due to the lack of sensors for monitoring each of the five girders, only girder 3 was monitored for an interior girder within the south and center spans. It appears that the neutral axis is positioned within the concrete slab or towards the upper flange indicating composite action is occurring.

Table 1. Average neutral axis (NA) locations from bottom flange of girder at mid-span [cm].

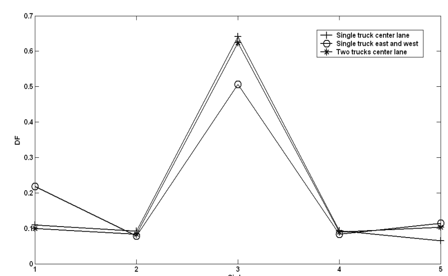
	Girder 1 (G1)	Girder 3 (G3)	Girder 5 (G5)
South Span	82.11	95.68	87.45
Center Span	79.91	92.18	92.76
North Span	92.20	N/A	84.02

4.2.2 Distribution and Impact Factors

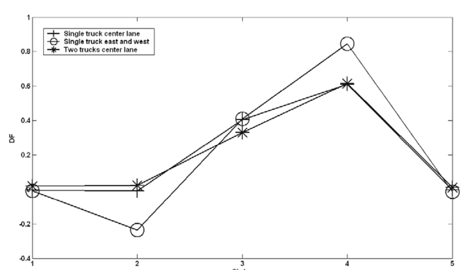
Load distribution factors are a measure of load transfer through the structure. As a means of safety, the load is typically shed to other bridge elements as to not overstress the primary load carrying member. For this to occur, the load is transferred transversely within the structure through the bridge deck and diaphragms. Figure 7 illustrate the load shedding characteristics within each of the three nearly identical spans based on the select loading conditions. Figures 7a-c display different behaviors based on identical loading conditions. The existence of damage or change in section properties within each of the spans could be the result of this difference. One such example of this damage is the presence of a restraint bearing of girder 3 in the center span; this is clearly depicted in figure 6(c). Ideally, an expansion bearing would allow for free rotation and longitudinal translation. However, the presence of negative strain in the bottom flange indicates rotational restraint exists. Upon visual inspection it was clear that the heavy amounts corrosion on many of the bridge bearings would likely cause some level of fixity to be present. The change in bearing restraint among the different girders is one possible cause of this differing response. These results suggest that the health of the structure has changed as identical loading cases on nearly identical span layouts should produce similar trend in the response. ON another note, the two load cases (in figures 7a-c) which have either one or two trucks in the center lane display very similar behaviors. This likely suggests that the transverse positioning of the load has a greater influence on the distribution factor than the load itself. Figure 7(d) demonstrates more clearly the load paths of the test vehicle in the north span under three load cases not necessarily identical to those illustrated in figures 7a-c. Load cases which have a single trick in the east or west lanes show higher loads in the primary girders supporting the west and east lanes respectively, where as the load case with a single truck in the center lane indicate a higher distribution in girders 3 and 4. It is apparent by this information that the load is distributing within the structure, however in some cases not significantly and perhaps below the expected level.



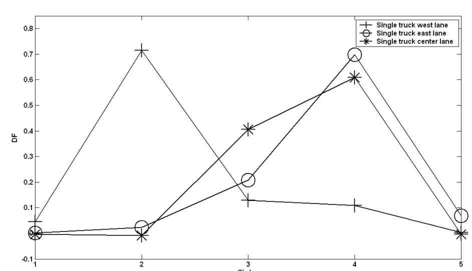
(a) South Span



(b) Center Span



(c) North Span



(d) North Span

Figure 7. Moment distribution factors at the mid-span of each span under different loading conditions.

5.0 CONCLUSION

A Wireless Sensor System (WSS) developed at Clarkson University was deployed on a three span simply supported bridge in New York State. The study focused on capturing both the modal and strain based characteristics of the superstructure. A total of ninety wireless accelerometers and strain transducers along with an additional nine wired strain transducers were installed with readings taken over a two day testing period. All measurements were sampled at a rate of 128 Hz in real time through two simultaneously run networks. Modal analysis based on the average normalized power spectral density revealed the first order natural frequencies of the spans were generally in the range of 8Hz to 13Hz. From these results, the first 9 lower order operational mode shapes were produced of the entire superstructure using stochastic subspace identification. Strain measurements provided neutral axis locations at the mid-span of the middle and two exterior girders of each of the three spans. The results conclusively show the presence of composite action between the girder and bridge deck. Moment distribution factors computed at the mid-span of each girder suggest load transfer throughout the superstructure. There did however appear to be certain anomalies among specific data within the center and south span based on the loading conditions, possibly due to deterioration or slight change in specific material or geometric properties among the spans. In addition, the presence of end bearing restraint indicates some level of fixity, likely due to the severe corrosion. This deployment clearly indicates the developed wireless sensor network is capable of periodic, schedule-based load testing.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the New York State Department of Transportation and, in particular, the Region 7 engineers and bridge maintenance crew for facilitating and assisting with the field testing. Additionally, the authors also wish to thank Professor Ratneshwar Jha and graduate students, Wei Chen and Jessica Rocheleau, and undergraduate students, Francis Dayamba and Sarah Marin, for their on-site assistance during the sensor installation.

REFERENCES

Aktan, A.E., Pervizpour, M., Catbas,N., Grimmelsoman, K., Barrish, R., Curtis, J., Quin, X. (2001) Information technology research for health monitoring of bridge system. London, UK, *Structural faults &Repair*. July 4-6.

Bridge Diagnostic Incorporated (BDI) (2008). Wireless Structural Testing System (STS-WiFi). World Wide Web. Online. Available at: http://www.bridgetest.com/products/bdi_sts-wireless.html. Accessed: 7 January 2008.

DeWolf, J.T., D'Attilio, P.F., Feldblum, E.G., and Lauzon, R.G. (2006). Bridge Monitoring Network - Installation and Operation. Connecticut Department of Transportation. Report No. CT-2217-F-06-10. December.

Federal Highway Administration (FHWA), (2007). Deficient Bridges by State and Highway System. Online. World Wide Web. Available at: http://www.fhwa.dot.gov/bridge/deficient.cfm. Date Accessed: 8 January 2009.

Gangone, M.V., Whelan, M.J., Janoyan, K.D. (Accepted for Publication) (2008). Deployment of a dense hybrid wireless sensing system for bridge assessment," Taylor & Francis. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*.

Hag-Elsafi, O, Kunin, J., (2006). Load testing for Bridge Rating: Route 22 over Swamp River. New York State Department of Transportation (NYSDOT), Special Report, February.

Lynch, J.P., Wang, Y., Loh, K.J., Yi, J-H., Yun, C-B. (2006). Performance Monitoring of the Geumdang Bridge Using a Dense Network of High-Resolution Wireless Sensors. Institute of Physics Publishing. *Smart Materials and Structures*. IOP publishing, UK. 15(2006). October. Pgs. 1561-1575.

Whelan, M.J. and Janoyan, K.D. (Accepted for Publication) (2009). Design of a Robust, High-Rate Wireless Sensor Network for Static and Dynamic Structural Health Monitoring. Sage Journals, *Journal of Intelligent Material Systems and Structures.* doi:10.1177/1045389X08098768

Whelan, M.J., Gangone, M.V., Janoyan, K.D., and Jha, R. (Under review) (2008a). Operational Modal Analysis of a Multi-Span Skew Bridge Using Real-Time Wireless Sensor Networks. Sage Journals, *Journal of Vibration and Control*.

Whelan, M.J., Gangone, M.V., and Janoyan, K.D. (Under review) (2008b). Highway Bridge Assessment using an Adaptive Real-Time Wireless Sensor Network, *IEEE Sensors*.