**Cover page**

# **Title:** Performance Monitoring of a Bridge Superstructure Using a Dense Wireless Sensor Network

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## ABSTRACT:

Performance monitoring of bridges is in great demand for existing and new structures alike. A large number of today's bridges are rated as structurally deficient due to significant deterioration requiring investigation of their structural health. Discussed in this paper is the deployment of a dense wireless sensor system on a short span integral abutment bridge superstructure located in St. Lawrence County, New York. The Wireless Sensor Solution (WSS) developed at Clarkson University's Laboratory for Intelligent Infrastructure and Transportation Technologies (LIITT) is designed specifically for diagnostic bridge monitoring, providing independent conditioning for both accelerometers and strain transducers in addition to high-rate wireless data transmission and is capable of supporting large-scale sensor arrays. During the deployment, strain and acceleration measurements are obtained simultaneously and in real-time at critical locations of the bridge under several loading conditions, including ambient environmental and traffic loading. Results from the strain data analysis aid to quantify the bridge static response, notably end fixity and load distribution along the girder length. Accelerometers provide the dynamic characteristics of the superstructure. An average normalized power spectrum is developed from acceleration measurements where the natural frequencies along with their corresponding mode shapes are extracted. The findings are compared to a developed analytical Finite Element Method (FEM) model based on the bridge as-built drawings. Results from the test deployment correlate well with the FEM model and the expected behavior for integral abutment bridge.

**Key Words:** Ambient, Strain, Acceleration, Wireless, Bridge monitoring, Integral abutment, Load testing

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## INTRODUCTION:

Many structures around the world are deteriorating due to environmental impacts, long term use and construction defects. Researchers are working to develop methods of structural monitoring to allow the complete and accurate assessment of structural performance in a non-destructive manner. With more than 27 percent of the 590,750 bridges in the United States classified as structurally deficient or obsolete [1], new diagnostic tools to locate and assess damage for repair is crucial. A common method of structural condition assessment by many state transportation agencies is through manual local and visual inspection techniques by at least one licensed professional engineer. However, due to the limiting constraints and subjectivity on the process, visual inspections alone are not always adequate since they do not provide a complete depiction of the true structural condition. Time constraints as well as lack of accessibility to hidden parts of the structure make it difficult to identify every such defect that may lead to eventual structural failure. In 2001, the Federal Highway Administration (FHWA) concluded a study which found that 56 percent of medium to short span bridges given an average condition rating were improperly assessed [2]. A robust monitoring system is needed to overcome the difficulty of determining structural defects due to the many constraints outlined as well as the subjectivity involved in the process [3].

Structural monitoring is a widely researched topic among many researchers today. A network of sensors collecting measurements and software to interpret the results combined with data analysis methodologies are the essential components of a strong system. Through the use of both accelerometers and strain measuring devices, the behavior of a structure under various loading conditions can be obtained. Accelerometers capture the dynamic characteristics of the structure under ambient and forced vibrations allowing, among other things, the determination of the modal properties (mode shapes, damping ratio and natural frequencies). Strain measurements provide insight into the performance of the structure by determining such behaviors as stresses, moments, impact factor, load transfer and stiffness that can either verify a design method or simply indicate the level of service life remaining in the structure. Whether utilizing global or local monitoring methodologies, providing a greater number of sensors and sensor types (i.e. accelerometers, strain transducers, thermocouples etc.) results in an improved overall representation to the structural performance. Currently, many state agencies such as the New York State Department of Transportation (NYSDOT) utilize load testing with strain transducers to measure the performance and capacity of a bridge [4]. Load distribution, dynamic impact factors, end fixity levels and composite action between the deck and girders are evaluated to illustrate the structural stiffness as well as load transfer and redundancy of the system. California Department of Transportation (Caltrans) employs accelerometers to measure the affects of seismic activity to many structures. This paper focuses on the measurement of both acceleration and strain of a short span integral abutment bridge in New York State using a developed wireless sensor system. As this deployment was the first with the developed system, an initial performance evaluation is of great interest.

## WIRELESS SENSOR DEPLOYMENT

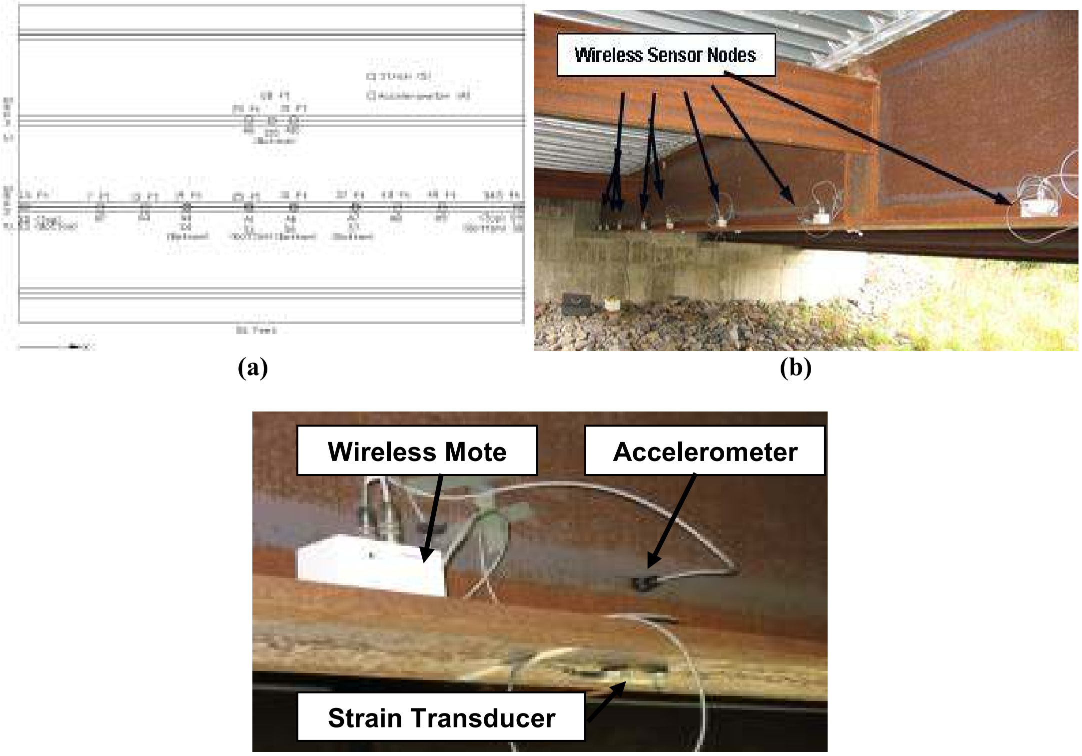
## Wireless Sensor Development

Performance monitoring methods are critical in assessing the performance and condition of a structure. With the rising demand for technologies to improve the accuracy of structural evaluations, newly devised methods to efficiently and effectively monitor the structure performance is sought. A Wireless Sensor System (WSS) which includes a dual axis accelerometer, strain transducer, and a custom conditioning board has been developed in the Laboratory for Intelligent Infrastructure and Transportation Technologies (LIITT) at Clarkson University. An accelerometer and strain transducer connected to a single custom conditioning board comprise one unit (node) that attaches to a mote, sending the signal wirelessly in packets to another mote connected to a CPU where the data is collected and processed by a custom software platform. A total of ten wireless units were developed and used in the monitoring. All ten units can be transmitting simultaneously in real time to a single mote which is externally connected to the CPU. For more information on the developed wireless system see [5].

## Bridge Deployment using Wireless Technology

The bridge instrumented in this deployment is the Wright Road Bridge over Trout Brook in the Town of Potsdam, New York which is under the jurisdiction of the St. Lawrence County Department of Highways (Fig. 1). The bridge was constructed in 2004 and is a 56ft span integral abutment bridge with four W36x135 girders spaced at 9 ft. Two equally spaced C15x33.9 sections serve as intermediate diaphragms between each girder in addition to MC8x20 end diaphragms. The roadway consists of a 14 in thick concrete deck. A low traffic volume and primarily light weight vehicles, such as cars, SUVs and pickup trucks, comprise the typical everyday bridge loading. Obtaining the maximum response of the superstructure was of utmost importance. Therefore, therefore strain transducers were deployed near the mid-span and ends where maximum strain measurements are likely to occur. A shift in the neutral axis location for additional stiffness contributions by the bridge deck to the girder stiffness were determined by placement of the strain transducers at the top and bottom flange at the ends. This configuration aided in giving a strain profile along the depth of the beam. The top flange of the mid-span was not monitored due to restrictions in sensor mounting. Two additional strain transducers were located at the quarter spans to determine if a change in inflection (curvature) could be detected. A total of eight strain transducers spaced at 6 foot intervals were placed along a single interior beam, with one additional sensor at the mid-span of the neighboring interior beam. This provides some insight into the load transfer to the neighboring beam. At the time of the deployment, one strain sensor was found to be malfunctioning thus leaving nine available for monitoring. Future papers will discuss a second deployment was completed in September 2006 with 20 units consisting of 11 strain transducers with single axis acceleration, and the remaining 9 units with dual axis acceleration measurements (40 channels total) [6].

For this exercise the vertical accelerations were measured simultaneously with strain measurements. Eight wireless sensors were instrumented at 6 foot intervals along the same interior beam as the strain transducers. The remaining two accelerometers were placed on the neighboring beam with the lone strain transducer. Figure 1 shows the sensor layout along the two interior girders along with a single node unit that includes the wireless mote, accelerometer, and strain transducer. This instrumentation plan allows for the determination of modal properties, in particular natural frequencies and mode shapes. All measurements from all 20 channels were sampled at an effective sampling rate of 151.7 Hz in real time at a 12 bit resolution.



(a) (b)

(c)

**Figure 1 (a) Sensor layout (b) field deployment of sensors on girder 2 (c) single sensor node**

## RESULTS FROM DEPLOYMENT

Despite the low levels of excitation, acceleration responses were still captured and the dynamic characteristics obtained. As expected, location six corresponding to Figure 1(a) and closest to the midspan, displayed the highest acceleration response as illustrated in Figure 2. Each of the thirteen tests runs 180 seconds (3 minutes simultaneous with strain measurements), where peaks above the noise symbolize a forced excitation such as from vehicle crossing as seen in Figure 2(b). Here a peak acceleration of 12 mg is shown likely corresponding to a heavier vehicle in comparison the other events in the time history.

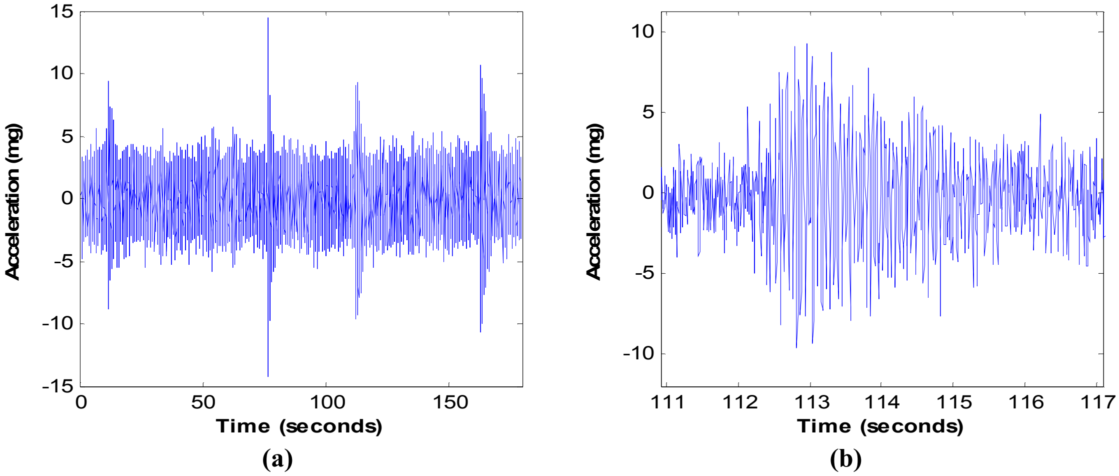


**Figure 2 (a) Typical acceleration response (b) Single vehicle response**

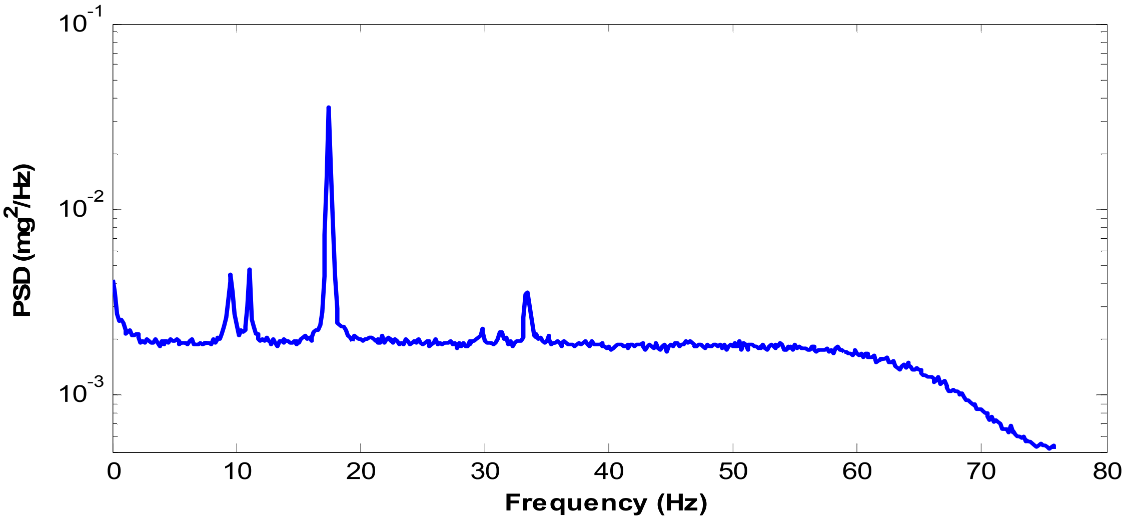


**Figure 3 Average Normalized Power Spectral Density**

The responses obtained from each of the acceleration time histories produced an average power spectrum of frequencies. The test captured six peaks in the spectrum, corresponding to the natural frequencies shown in Figure 3. This average normalized power spectral density plot was produced from all measurements taken within the seven time tests. The natural frequencies are relatively high and amplitudes of the spectrum low, indicating the structure is stiff. This can also be observed in Figure 4 where the first three mode shapes representing the interior monitored portion of the bridge superstructure were extracted from the data. Prior to deployment, a three-dimensional solid Finite Element Method (FEM) ALGOR model of the structure was constructed to compare the experimental results to the theoretical model. This model was not calibrated to the exact field conditions of the structure. It was however based on the as-built drawings provided by the county and was used to provide an approximation as to the natural frequencies to be expected in the field prior to deployment.

Upon examination of the results, the experimental findings followed the model well. Modes 1 and 3 depict the first two vertical bending modes, with mode 1 showing ever so slight twisting near the center as beam 2 shows slightly higher response than beam 3 towards the midspan. Mode 3 however illustrates the responses of both instrumented girders to be fairly identical. Mode 2 purposes that some twisting is occurring towards center of the bridge, as beam 3 is displaced higher than beam 2. This was likely excited by a vehicle traveling close to the railing which helps to induce this mode at a greater magnitude.

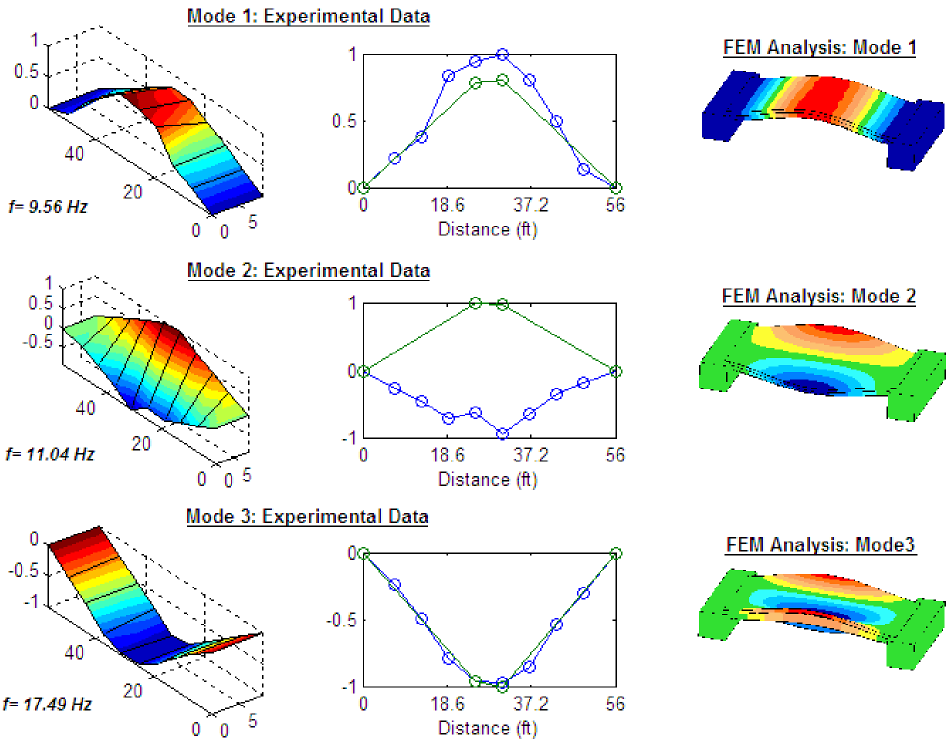


**Figure 4 Experimental Mode Shapes and Comparison with FEM Analysis**

Due to the rural location of the structure, lower levels of ambient excitation were encountered. Nonetheless, expected responses from many of the strain sensors were captured at their respective locations. Thirteen separate 3-minute intervals of measurements were taken where any loading within the time span was recorded. A sample of typical recorded strain measurements are shown in Figure 2. Channels 1, 4, 6, and 7 are located within the inflection boundaries, displaying positive strain peaks within the range of 3 to 5 micro strains for each of the thirteen tests, corresponding to a vehicle crossing. As with most bridge superstructures, locations near the midspan produce maximum strain responses. This particular integral abutment structure is no different. Figure 5 illustrates that the transducer nearest the midspan (channel 1 at 25 feet from the south abutment) has highest strain magnitude. Furthermore, channels 4 and 7, both located 19 feet from the supports, each demonstrate very similar strain responses while channel 6 (31 feet from south end) is greater than 4 and 7. In short, the strains beyond the inflection points are increasing as they approach the mid-span. It is expected that with an integral abutment design, negative strains are present at the bottom flange near the supports. However, due to the remaining channels recording predominantly noise, or excessively low strain readings, these were hard to determine. More conclusive results would be obtained with larger weight vehicles, such as those typically used for load testing, as the low strains are not adequate for obtaining load testing values.

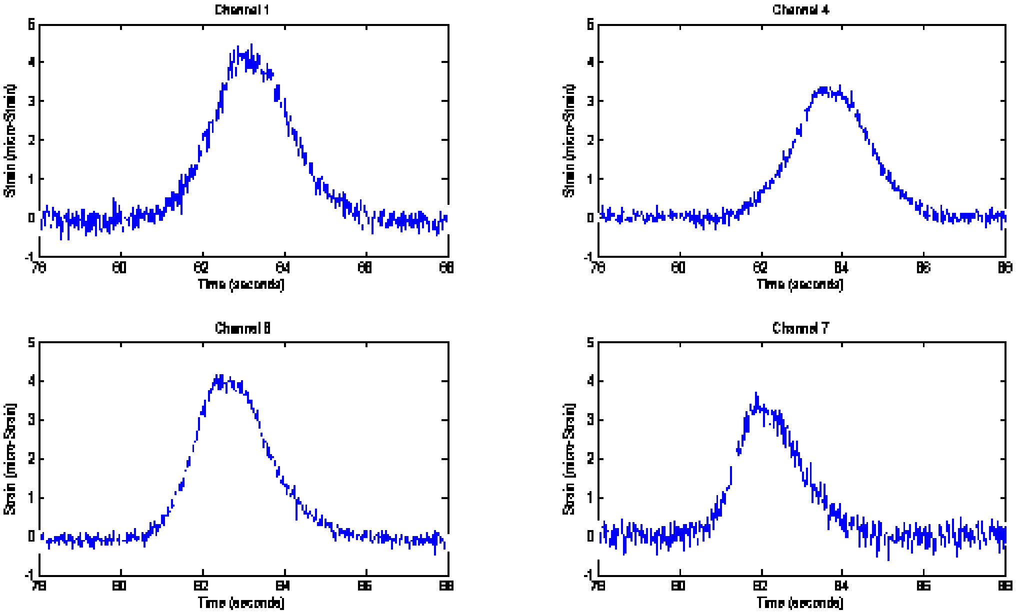


**Figure 5 Typical strain responses within bridge inflection points**

## CONCLUSION

Performance monitoring is becoming ever more necessary due to the rapid rate of structural deterioration of much of today's infrastructure. As a result, new and improved developments in sensor technology are sought to aid in producing optimal results. A Wireless Sensor System (WSS) developed at Clarkson University was deployed on an integral abutment bridge. Due to the low excitations produced through ambient loading conditions, small magnitudes of accelerations and strains were captured. Nonetheless, the results obtained depicted the typical behavior of an integral abutment design. However, future tests with larger test vehicles at or near service load conditions are recommended for acquiring more definite results, especially for load testing (strain) purposes. The dynamic response produced the six natural frequencies (first three were presented) with their corresponding mode shapes then compared to the theoretical shapes produced from a finite element analysis model. The results suggest the structure to be very stiff as typical of a short span integral abutment structure. The WSS presented in this paper demonstrated its capabilities to obtain measurements that can be later used with proper Structural Health Monitoring (SHM) methodologies for damage detection.

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## REFERENCES

1. Report Card for America's Infrastructure (2005). American Society of Civil Engineers (ASCE). http://www.asce.org/reportcard/2005/page.cfm?id=22. Accessed July 15, 2006.

2. Phares, B.M., Rolander, D.D., Graybeal, B.A., Washer, G.A. (2001) "Reliability of Visual Bridge Inspection." *Public Roads*. April.

3. Frasier, Michael. (2006) Development and Integration of an Integrated Framework for Structural Health Monitoring, Ph.D. Dissertation, University of California San Diego.

4. Hag-Elsafi, O, and Kunin, J., (2006) *Load testing for Bridge Rating: Route 32 over Plattekill Creek.* New York State Department of Transportation (NYSDOT), Special Report, February.

5. Whelan, M.J., Fuchs, M.P., Gangone, M.V., and Janoyan, K.D. (2007) "Development of a Wireless Bridge Monitoring System for Condition Assessment using Hybrid Techniques." SPIE Smart Structures Symposium, San Diego, California, March 19-22.

6. Whelan, M.J., Gangone, M.V., Janoyan, K.D., Cross, K., Jha, R. (2007) "Reliable high-rate bridge monitoring using dense wireless sensors arrays." 6th International Workshop on Structural Health Monitoring, Stanford, California, Sept. 11-13.