MPC-366 (Year 2)

January 1, 2012- December 31, 2013

Project Title:
Structural Health Monitoring of Highway Bridges Subjected to Overweight Trucks, Phase I – Instrumentation Development and Validation

University:
University of Wyoming

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Research Needs:
State DOTs in the West are under increasing pressure to permit and route overweight trucks transporting machinery and equipment for the energy sector through their state and interstate highway systems. DOT engineers are called upon daily to rate their bridges for overweight trucks to determine appropriate truck routing and to assess the impacts of the trucks on bridge safety and durability. Many of these overweight trucks have nonstandard configurations, which further complicates the rating and permitting process. Hence, it is critical that bridge engineers in the DOTs develop confidence that their bridge analysis and rating software accurately predicts the response of bridges to overweight trucks, especially for those bridges on the most frequently traveled routes. This confidence can be gained through the proposed project, in which software analysis and rating results for overweight trucks will be correlated to direct field measurements of the response of bridges when loaded by those same trucks.

Research Objectives:
The long-term objectives of the proposed project are to develop, install, and operate a field instrumentation package for structural health monitoring (SHM) of bridges subjected to overweight trucks and to correlate field performance data to the behavior of the bridges predicted by analysis and rating software. The field instrumentation package will incorporate use of optical fiber sensors to monitor strains at critical locations in bridges that are considered most vulnerable to overweight truck loads and are most difficult to effectively rate with currently used software.

Phase I of the project will involve a laboratory investigation, the objectives of which are to develop the instrumentation package, remote data collection, processing, and transmission capabilities, and field installation and operations methods suitable for long-term SHM of bridges in remote locations. Methods appropriate for both steel and concrete girder bridges will be developed, but the primary emphasis will be on SHM of steel plate-girder bridges. The monitoring system will be capable of observing bridge behavior under both static and dynamic (wheel impact) loadings. Phase I is expected to have a duration of two years.

Phase II of the project will extend the laboratory developments to field application and operations. It will further include correlation of field measurements with analysis results from bridge rating software. The monitoring system will be particularly valuable for assessing the effects of overweight trucks with unusual configurations, the majority of which serve energy development in the West. These trucks often have wide loads, a condition that increases the importance of accurate determination of wheel fractions. Moreover, during inclement weather conditions, road closures on the interstate highway system (I-80 in particular) cause long back-ups of trucks. When the closures are lifted, it is common for long trains of trucks to progress nearly bumper to bumper, filling all traffic lanes as travel resumes. Such situations raise serious questions about the possibility of bridge overload and durability under high-density truck traffic with normal configurations and loads. Phase II will have a duration of at least two years in order to provide the opportunity to observe a sufficient number of overweight trucks or high density traffic events and to refine the operation and durability of the SHM network. Continuation of Phase II to incorporate wide-ranging installation of sensing networks on critical bridges will be pursued.

Research Methods:
In Phase I of the project, instrumentation, packaging, installation techniques, and remote data retrieval for Fiber Bragg Grating (FBG) sensors will be developed in the laboratory. FBG sensors have been selected for this application since they possess several advantages over alternative sensor technology. Some of these advantages include the following (Kreuzer, 2007).

- FBG sensors are effective in measuring strain to a high level of resolution. Changes in strain as small as 1 $\mu\varepsilon$ can be observed with suitable interrogation instruments and signal processing techniques. The sensors can further measure very high strains, in excess of 10,000 $\mu\varepsilon$, thus increasing the likelihood that they will continue to function in the event of severe damage, such as due to vehicle collision.
- FBG sensors are capable of high scan rates using relatively low-cost interrogation instruments. Frequency response rates of 5 kHz are easily achieved, allowing accurate determination of wheel impact factors.
- FBG sensors are immune to electromagnetic interference, which might otherwise limit the environments in which they can be used.
- FBG sensors can be interrogated over long distances (in excess of 5 km) without loss of signal strength and resolution.
- Multiple (50 – 100) FBG sensors can be located on a single optical fiber and interrogated with a single electronic device.
- FBG sensors, their interrogation instrumentation, and data communications equipment consume relative low power, enabling an installation to function off-grid, using for instance a power supply consisting of only small solar cells and an automobile battery.

The use of optical fiber sensors for SHM of bridges has been an active area of research for more than a decade. Developments in sensor packaging (Leng, et al, 2005; Zhou, et al, 2003), interrogation instrumentation (Mendoza, et al, 2007), and data processing techniques (Doornink, et al, 2006; Zhou, et al, 2003) have given researchers confidence in the effectiveness of FBG sensors for field applications. The basic principles of SHM with FBG sensors are well known (Ansari, 2007; Kreuzer, 2007). Many successful field installations of FBG sensor networks have also been reported. These include proof of concept and individual bridge performance monitoring (Casas & Cruz, 2003; Lopez-Higuera, 2005; Heininger et al, 2011), special-purpose installations associated with bridge retrofit (Doornink, et al, 2006), and SHM of unique bridge designs (Calvert & Mooney, 2004). However, none of the reported field studies addresses the objectives of the proposed research – to couple real-time data from the sensor network to the results of bridge analysis and rating software to improve bridge engineers' ability to safely route overweight trucks.

The Phase I laboratory investigation will include the following primary tasks.

1. Development of optical-fiber packaging or other protection mechanisms suitable for installation in the target environments. Both steel and concrete girder bridges will be considered, with emphasis placed on girder-line response. Considerations will include the following sub-tasks.
   a. Protecting the optical fiber from damage due to the harsh environment and possible vandalism.
   b. Positioning and bonding optical fibers to the host girder material. The bonding process must assure effective strain transfer from the host material to the optical fiber in the vicinity of the FBG sensor.
   c. Repairing or replacing damaged optical fibers and sensors that do not survive the conditions in step 1.a.
   d. Compensating for temperature sensitivity of the FBG sensors, likely achieved through use of companion unbonded sensors.
2. Development of a low-cost, compact, and energy-efficient instrumentation package for interrogating the sensor network. It is feasible to design and fabricate custom instrumentation for the target applications at a lower cost and in a more appropriate form factor than might otherwise be acquired from commercial sources. This approach will be essential to achieving a sensing network that is easily stored and protected at the bridge site and uses a small, compact and rechargeable power supply.
3. Development of data collection, processing, and transmission capabilities. An FBG sensor network on a bridge will have the capacity to collect an overwhelming volume of data, so much so that data storage and transmission could easily become a constraining bottleneck to the performance of the network. To avoid this bottleneck, real-time data processing will be needed to convert the data collected by the interrogator into behavior parameters that are of value to the bridge engineers at the state DOTs. Among others such parameters may include strains, stresses, accelerations, vibration histories, damping ratios and impact factors. The volume of even these behavior parameters could become overwhelming unless some control is provided to synchronize the parameters with critical events, such as the passage of an overweight truck that has just been routed over the bridge, and then trigger delivery of the parameters to the DOT offices. For this project a general performance specification for real-time data analysis will be developed in cooperation with bridge engineers at the Wyoming Department of Transportation. Design and implementation of software to satisfy the performance requirements will complete this task.
4. Validation of tasks 1, 2, and 3 will be performed in the laboratory using mock-ups of bridges having steel and concrete girders. Pseudo-static and dynamic loading protocols, intended to simulate slow-moving and high-speed truck traffic, will be applied to the mock-ups to excite the FBG sensor network. Observed response will then be compared

to detailed analysis results to confirm the function and efficacy of the SHM system. Undoubtedly modifications to the three major elements of the system outlined in tasks 1, 2, and 3 will be needed to refine and enhance system performance to meet the needs and expectations of bridge engineers.

5. Investigators have reported that FBG sensors must be pre-tensioned prior to installation so that, if the host structure is subjected to in-service compressive strain, the sensors will simply relieve some amount of pre-tension, rather than experience a net compressive strain. Spurious compression-strain response of FBG sensors has been attributed to possible micro-bucking of the optical fibers, thus rendering the sensor output as a measure of host-structure strain unreliable. This task will involve an attempt to optically observe the deformation of the optical fiber loaded in compression to determine if micro-buckling does indeed occur. If such behavior is observed, the study will be continued to determine means by which micro-bucking can be prevented, thus allowing the sensors to accurately respond to compressive strain.

Expected Outcomes:
Tasks 1, 2, and 3 are expected to result in tangible outcomes that will be appropriate for conference presentations, such as at the TRB annual meeting, and journal articles. As an applied-research project, the outcomes of the project will be directly applicable and transferrable to bridge engineers at state DOTs as well as engineering service providers who work in the bridge sector and more broadly in SHM. Tangible products of the research will include the following.

1. A practice manual for installation of optical fiber sensor networks on highway bridges. Included will be techniques for protecting the fibers and the interrogation equipment from damage, details necessary to assure effective strain transfer from the host material to the FBG sensor, methods for repair of damaged fibers, and approaches to separating strain observations due to mechanical load from those due to temperature change.
2. Schematic design and fabrication guidelines for special-purpose instrumentation to interrogate the sensor network and collect the sensor response. The points of emphasis will include high-speed data acquisition and low power consumption.
3. Data analysis software designed and implemented to efficiently deliver system response parameters that are of direct use to bridge engineers. Appropriate software design standards and protocols will be employed to assure that the resulting applications will be portable and maintainable well after the original developers have moved on to other endeavors.

The outcome from task 4 will be a functional SHM system for highway bridges. The primary tangible benefit will be to bridge engineers in helping them refine their understanding of bridge performance relative to the predictions they obtain from their analysis and rating software. The system should provide assistance in evaluating the accuracy of their rating procedures as well as predicting the long-term durability of the bridges in their inventories.

Task 5 is expected to produce greater understanding of the compressive-strain behavior of FBG sensors. It will aid this project as well as other investigators in proper utilization of the sensors in areas of the host structure expected to experience compressive strain.

Relevance to Strategic Goals:
The proposed project will make direct positive contributions to the following strategic goals.

1. State of Good Repair: An effective SHM system for highway bridges will, over time, improve the ability of bridge engineers to predict the effect that overweight vehicles will have on the condition of their bridges. As the engineers received feedback on bridge performance to confirm or recalibrate their rating methods, they will have the capability to predict long-term durability of bridges. They will also be able to more effectively route overweight trucks and also specify appropriate reconfigurations of trucks that would otherwise not be permitted on certain routes.
2. Safety: Accurate real-time monitoring of bridge response will improve the operational safety of bridges during overload events by controlling the magnitude of the overload. Long-term safety will also be enhanced by use of the monitoring system to identify and quantify unanticipated overload events. Further, increased precision in defining the weight distribution in overweight trucks plus refinements in monitoring bridge response will reduce the inherent randomness in the demand (applied loads) as well as the variability in structural capacity to permit more refined predictions of bridge performance.
3. Economic Competitiveness: The proposed SHM system using relatively low-cost equipment with low power demand will provide the initial economic advantage to the project. The second advantage is in improved predictions of bridge durability and life-cycle. Effective scheduling of inspections and maintenance will be facilitated by an accurate and easy-to-use sensing network on the bridge. With suitable experience and calibration of the sensing network, engineers will be able to observe changes in bridge response that might suggest deterioration or damage, thus prompting more timely inspection and maintenance work.

Educational Benefits:
This project will employ two masters-level graduate students and two undergraduate students. The graduate students will pursue thesis research and the undergraduates will be hired on an hourly basis to participate in fabrication of instrumentation, experimental testing of FBG sensor behavior and implementation of software described in tasks 2 and 3. Over the long term the outcomes from this project may be appropriate for inclusion in a graduate level course (CE 5270 – Highway Bridge Engineering) at the University of Wyoming.

Year 1 Progress:
Progress in year 1 consisted principally of the completion of Tasks 0, 1a, 1b, and 1d. Results of these tasks are reported in the MS thesis by Mr. Daniel Maurais. That work has been distilled into a manuscript for a journal paper entitled: *Strain transfer behavior of notch-embedded fiber Bragg gratings*, which is in review for publication in Smart Materials and Structures. Preliminary work on Task 4 was initiated in year 1 but continues into year 2.

Year 2 Tasks:
Progress on Tasks 1b, 2 and 3 was delayed, because our co-investigator, Mr. Hilmar Heininger, had a change in his personal and professional lives and decided to remain in Germany. He will no longer be involved with the project. Instead we have added a UW graduate student in electrical engineering to the project to assume the duties previously assigned to Mr. Heininger.

In addition an undergraduate research assistant has been added to the project to investigate unexpected behavior of Bragg gratings when loaded in compression. A new task has been added to the project for this study.

Work Plan:
The primary research tasks associated with the work plan for this project are described in the foregoing section entitled Research Methods, as the tasks themselves are tightly integrated with the methods to be applied. Those tasks as well as a literature review and additional reporting and technology transfer milestones are summarized below. In the following schedule the symbol “>>” indicates that a task is underway. The letter “R” indicates the scheduled time for preparation of a draft report. The letter “P” indicates preparation of a conference or journal paper.

0. Literature review
1. Development of optical-fiber packaging
    a. Protecting the optical fiber from damage
    b. Positioning and bonding optical fibers to the host girder material
    c. Repairing or replacing damaged optical fibers and sensors
    d. Compensating for temperature sensitivity of the FBG sensors
2. Development of a low-cost, compact, and energy-efficient instrumentation package
3. Development of data collection, processing, and transmission capabilities
4. Validation of tasks 1, 2, and 3
5. Investigate the behavior of FBG sensors loaded in compression
6. Hold laboratory training workshop for DOT bridge engineers via UW’s LTAP.

Phase I Project Schedule

	Month after project start											
	Year 1											
Task	1	2	3	4	5	6	7	8	9	10	11	12
0.	>>	>>	>>	R								
1.a.		>>	>>	>>	>>	R						
1.b.				>>	>>	>>	>>	R				
1.c.						>>	>>	>>	>>	R		
1.d.				>>	>>	>>	>>	R			P	
2.		>>	>>	>>	>>	>>	>>	>>	>>	R	P	
3.				>>	>>	>>	>>	>>	>>	>>	R	P
	Year 2											
4.	>>	>>	>>	>>	>>	>>	>>	>>	R	P		
5.	>>	>>	>>	>>	>>	>>	>>	>>	R			P
6.											>>	R

Project Cost:
Total Project Costs: $ 111,452
MPC Funds Requested: $ 39,480
Matching Funds: $71,972 Source of Matching Funds: WY LTAP

TRB Keywords:

Bridge engineering, Durability, Fiber optics, Instruments for measuring deformation or deflection, Monitoring systems, Structural analysis, Trucks, Wheel loads

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