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SEISMIC MONITORING OF BRIDGES IN BRITISH COLUMBIA, CANADA

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ABSTRACT

This paper provides an overview of the bridge instrumentation program in British Columbia and illustrates the current approach to instrument and monitor bridges by reference to a recent case study. The BC Ministry of Transportation and Infrastructure and the University of British Columbia have recently embarked on a program to instrument key structures to provide confirmation of seismic capacity, assist in focusing retrofit efforts, detect damage from any cause and provide rapid damage assessment of those structures following a seismic event. The data from this instrumentation will be capable of remote configuration and will automatically upload via the internet. As part of this collaboration effective damage detection algorithms that will provide reliable intelligence close to real time have been developed and implemented. This paper provides an overview of present status of the bridge instrumentation program in BC and illustrates the current approach to instrument and monitor bridges in the province.

Introduction

The west coast of BC lies in Canada's highest seismic zone under threat of three different types of large, highly destructive earthquakes. The British Columbia Ministry of Transportation (MoT) is responsible for 400 km of provincial Disaster Response Routes. The loss of any portion of one of these routes could significantly impact emergency response efforts and negatively affect public well being. The Ministry maintains 900 structures in the highest seismic zones, many of which are vulnerable to extensive damage in even a moderate quake and potential collapse in a major earthquake. The loss of the use of several structures would not only have immediate impact on public well being and the ability of emergency vehicles to respond effectively, but would also cripple the economic recovery of the region. The effects would be felt across the nation and for many years into the future.

The better the information on which areas, structures and facilities are most vulnerable, the better planning and preparation can be done. By identifying those structures and facilities most susceptible to seismic forces, decision-makers can do effective risk management. Fast, ac-

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curate field intelligence immediately following an earthquake can ensure the most effective deployment of vital services and mitigate damage to the built environment.

In recent years, the MoT has been instrumenting bridges in collaborating with the Earthquake Engineering Research Facility (EERF) of the University of British Columbia (UBC). Presently, seven structures have between six and eighteen accelerometers and two structures have a limited number of strain gauges. Three of these structures have recorded motions from earthquakes in the last decade. Only two structures upload data to an internet site. Twelve more structures are scheduled for instrumentation over the next four years.

MoT and UBC have embarked on a program called **Smart Infrastructure Monitoring System (SIMS)** to instrument key structures to provide confirmation of seismic capacity, assist in focusing retrofit efforts, detect damage from any cause and provide rapid damage assessment of those structures following a seismic event. The data from this instrumentation will be capable of remote configuration and will automatically upload via the internet. As part of this collaboration effective damage detection algorithms that will provide reliable intelligence close to real time have been developed and are now being implemented.

The bridge selected to illustrate the current approach to instrument bridges in BC is the Ironworkers Memorial Second Narrows Crossing in Vancouver, BC. The structure is 1292m long and it is divided, from North to South, into three components: a multi-span approach concrete viaduct, a multi-span approach steel truss supported on isolation bearings, and a cantilever steel bridge. The complexity of the structure presents significant challenges for selecting the most suitable instrumentation that can provide not only useful information in the case of an earthquake in the region, but also useful information for an on-line structural health monitoring program to evaluate the behavior of the bridge during normal operating conditions.

Goals and Objectives of the SIMS Project

The Goals of this Project are to:

1. develop and implement a real-time seismic structural response system to enable rapid deployment and prioritized inspections of the Ministry's structures; and
2. develop and implement a health monitoring program to address the need for safe and cost-effective operation of structures in BC.

This Project will help transform the current practice of inspecting and evaluating all structures after an earthquake to a more rational and effective one that makes effective use of state-of-the-art sensing technology with fast and efficient techniques for data analysis and interpretation. Inspections can then be focused and prioritized to maximize the effectiveness of scarce resources. This Project will further provide ongoing structural condition monitoring for impact or deterioration to enable timely inspection and intervention.

The Objectives of this Project are to:

1. develop and implement a cost-effective, reliable Structural Health Monitoring (SHM) technology that makes effective use of sensors and broad band digital communications for remote monitoring of structures subjected to dynamic loads;

2. identify and implement effective algorithms for system identification, model updating and damage detection suitable for remote monitoring of structures subjected to seismic forces and condition changes due to deterioration or impact; and
3. develop an integrated decision support system that incorporates geographical information and information about ground shaking and structural performance of a portfolio of remotely monitored structures distributed throughout the province. This system will include decision-making tools that will expedite the process of prioritization, risk assessment and damage evaluation to assist decision-makers with post earthquake response and recovery options.

The state-of-the-art technology to be developed by the EERF will be used to detect, analyze and localize damage to structures and transmit the data in real time via the Internet and display in animated and static web pages as appropriate for use by the Province and UBC. The alert systems and public access web pages will display real time seismic data from the BC Strong Motion Network to provide input to assessments for non-instrumented bridges. They will also provide other agencies, emergency responders and engineers with instantaneous situational awareness. Either structural deterioration or impact damage that results in a pre-set level of change in readings of the instruments will trigger an alert as well as triggering a full diagnostic evaluation automatically. The structural condition information and displays will be accessed only by designated parties. The distribution list for alerts will be based on the type of alert and source of damage. Seismic damage will have a wider distribution but condition and impact alerts from a single structure will go only to selected institutions.

The data collected will be analyzed at the EERF with off-site backup, and the results will be used by the Ministry to make decisions about the operability of the monitored structures after a significant seismic event.

Project Schedule and International Collaborations

The monitoring project started in the summer of 2009 and should be fully operational by the spring of 2010. During this period of time three important milestones need to be completed: 1) Evaluation and selection of damage detection algorithms; 2) Development of software and acquisition of hardware to implement a real-time Internet-base monitoring system; and 3) Commissioning of the system and remote access to existing instrumented structures.

Because of the complexity of this project, collaboration has been formally established with institutions and companies with different types of expertise. Interaction with suppliers of monitoring equipment for bridges has also been established. The key collaborators are:

1. Pacific Geoscience Centre of Geological Survey of Canada in Sidney, British Columbia. The SIMS software will interact with the strong motion instrumentation network in British Columbia and will facilitate exchange of data with this network so that concurrent information of ground motion data and bridge motion data can be obtained through the monitoring system.
2. A partnership of Structural Vibration Solutions A/S (SVS) of Aalborg, Denmark, Dynamic Design Solutions (DDS) of Leuven, Belgium and the Institut National de Recherche en Informatique et en Automatique (INRIA) – Bretagne Atlantique, Rennes Ce-

dex, France is responsible for developing the key software components that will be the core of the structural health monitoring project and provides a seamless interface between the tools developed by each of these organizations.

Components of SIMS

This section provides a general description of the main components of monitoring system. The functional components of SIMS will perform structural assessments in two fashions: a) monitoring before and after an event (see Fig. 1), and b) evaluation of performance of the instrumented bridges immediately after a significant earthquake (see Fig. 2). Customized graphical interfaces will permit a fast and effective identification of the structures that have recorded strong motion data or that are behaving in an uncharacteristic manner. Figures 3 through 5 show samples of information screens that will be part of the graphical interface system.

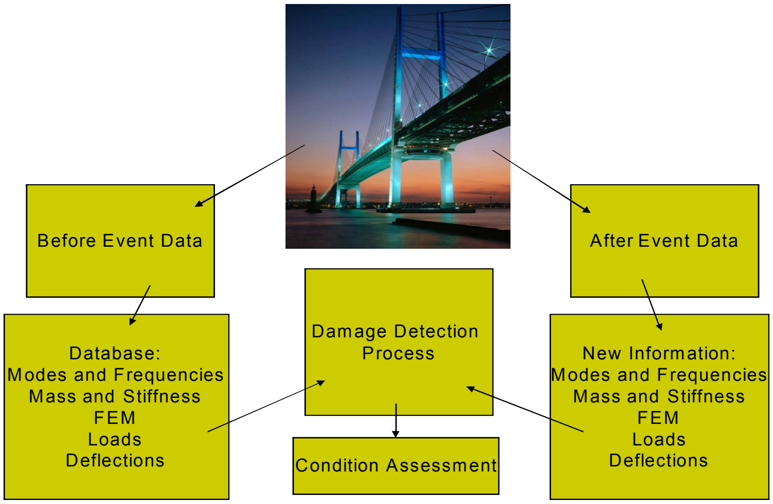


Figure 1. Structural assessment pre and post event

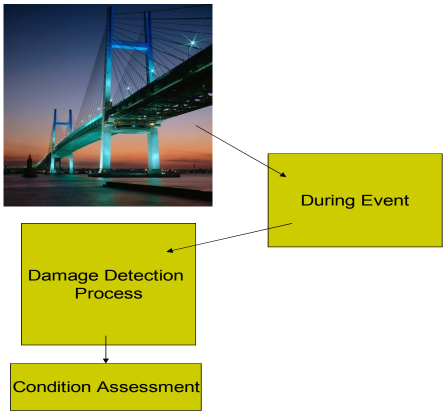
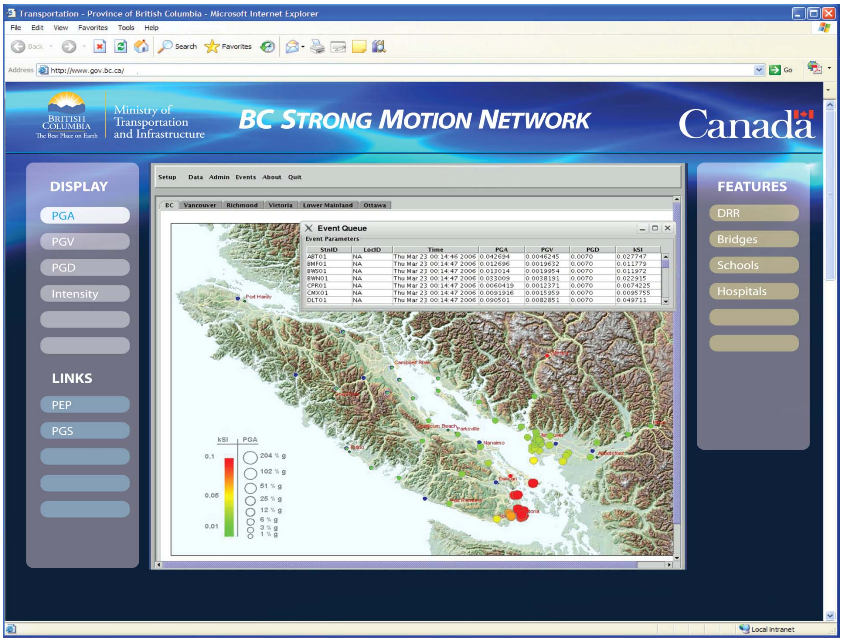


Figure 2. Structural assessment during event.



StnID	LocID	Time	PGA	PGV	PGD	kSI
ABT01	NA	Thu Mar 23 00:14:46 2006	0.042694	0.0046245	0.0070	0.027747
BMF01	NA	Thu Mar 23 00:14:47 2006	0.012696	0.0019632	0.0070	0.011779
BWS01	NA	Thu Mar 23 00:14:47 2006	0.013014	0.0019954	0.0070	0.011972
BWN01	NA	Thu Mar 23 00:14:47 2006	0.033009	0.0038191	0.0070	0.022915
CPR01	NA	Thu Mar 23 00:14:47 2006	0.0060419	0.0012371	0.0070	0.0074225
CMX01	NA	Thu Mar 23 00:14:47 2006	0.0091916	0.0015959	0.0070	0.0095755
DLT01	NA	Thu Mar 23 00:14:47 2006	0.090501	0.0082851	0.0070	0.049711

Figure 3. Main screen of SIMS showing the levels of shaking caused by a simulated Magnitude 6 earthquake near Victoria, BC.

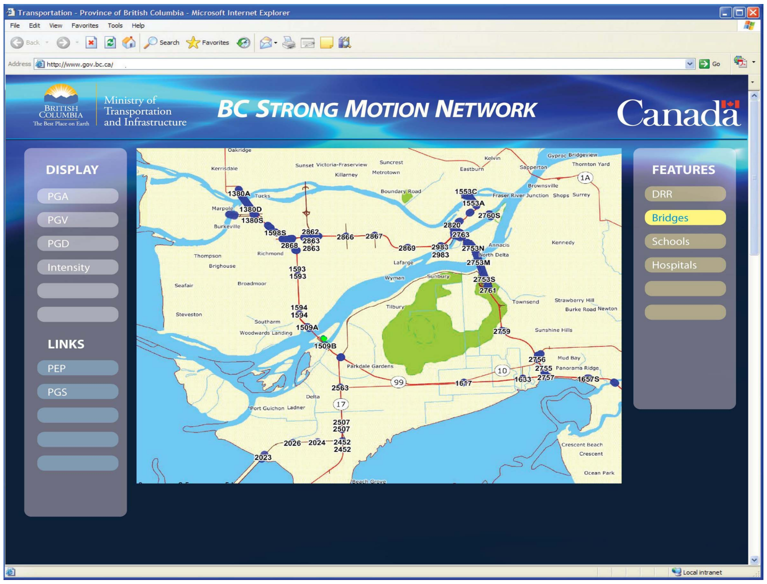


Figure 4. After clicking the features for bridges, the map shows the bridges in the region that have recorded motions.

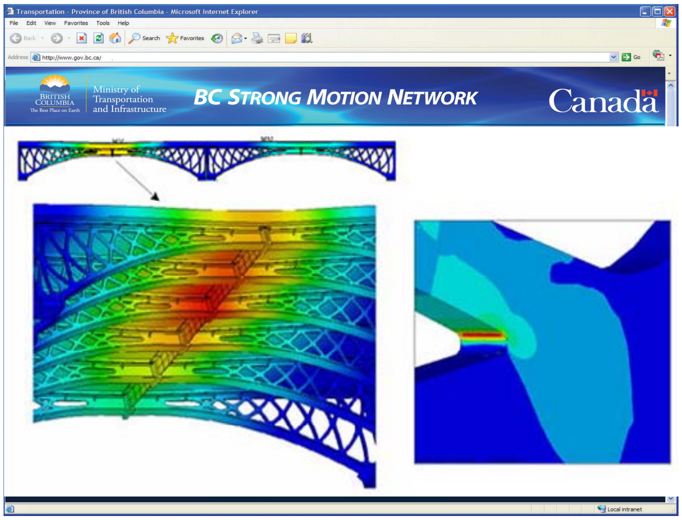


Figure 5. Example of screen showing the results of the damage assessment obtained from the analysis of the data obtained at the bridge.

From a user point of view the system is divided in two: 1) a public available Shake Map View of a selected region showing levels of ground shaking and with general performance indexes indicating the status of the bridges being monitored, and 2) a restricted Shake Map View displaying detailed information about the health of the bridges being monitored. From this map there will be access to information about the individual structures through a Structure Inspection View interface (SIV).

The types of analyses available in the SIV are listed in Table 1 below. The speed of getting the latest updated information is the most critical issue and the system will take this into account. During an event sending large data packages will be avoided so as not to overload the network. The recorded event data will then be transmitted to the central data base when the network activity allows it. The public available GUI will ultimately have its own server, internet connection and its own local data storage that receives a copy of the latest information when there is an event.

The SIMS system is a Supervisory Control and Data Acquisition (SCADA) system consisting of the following subsystems: 1) Public available and restricted web-based Graphical User Interfaces capable of displaying relevant information. 2) One SIMS1 supervisory computer administrating the traffic between sensors, remote processing computers, and data base. 3) Remote SIMS2 processing computers connecting the on-site monitoring equipment to the system. These computers will analyze the measurements to produce damage indicators and OMA results and should be as close as possible to the data acquisition system. 4) One or more SIMS3 computers used for post-processing such as FE updating and trend analysis.

All information in the system will be stored in a single database. The data base will keep a list of all the monitored structures. When a specific structure is selected in the Shake Map the details are read from the corresponding table in the data base. The information is stored in a Structure Information Table. Regardless of the location of the sensors (on the ground or on structures), the sensors and data acquisition parameters are handled and stored in the same manner.

The data base will store all the settings that influence the way the installed measurement hardware will record data. The will be a Data Acquisition Table that will hold a list to all sensors. Each sensor is described in a Sensor Information Table.

The way to set up triggers and scheduled measurements are administrated by a Trigger Information Table and a Measurement Information Table. Each recorded event is stored in an individual record in the data base, and the analyses made on the measurements are stored in Analysis Information Tables. The recorded data will be stored as binary large objects. The backup of all the data and information will as such be based on synchronization of two or more databases located at different sites.

Table 1. Types of analyses available in SIV.

Type	Analysis Display Options	Description	Avail. In View
Health Status	Damage indication from event data, INRIA and OMA damage indication on post event data, damage indication using updated FE.	Indicate the areas of the structure where health is deteriorated using contour colors.	3D, Report
Reference FE	Displacements, stresses, mode shapes, MAC diagram.	Display results of the reference FE model.	3D, Report
Updated FE	Displacements, stresses, mode shapes, MAC diagram.	Display results of the updated FE model.	3D, Report
FE Correlation Updated versus Reference Model	Displacements, stresses, mode shapes, MAC diagram.	Compare the updated FE model with the reference model.	3D, Report
FE trend analysis	Mode shapes, natural frequencies, stress and displacement for selected DOF's.	Perform a historical trend analysis from reference state to currently selected event. Optionally, perform a linear prediction into the future.	2D, Report
Reference OMA	Mode shapes, MAC diagram, Processed Spectral Data, Stabilization Diagrams.	Display results of the reference OMA analysis.	3D, 2D, Report
Updated OMA	Mode shapes, MAC diagram, Processed Spectral Data, Stabilization Diagrams.	Display results of each of the OMA analyses performed on the post event measurements.	3D, 2D, Report
OMA trend analysis	Mode shapes, natural frequencies, damping ratios	Perform a historical trend analysis from reference state to currently selected event. Optionally, perform a linear prediction into the future.	2D, Report
Damage Indicator trend analysis	Damage Index Method (DIM), drift, INRIA	Perform a historical trend analysis from reference state to currently selected event. Optionally, perform a linear prediction into the future.	2D, Report

Instrumentation of the IMSNC

The Ironworkers Memorial Second Narrows Crossing (IMSNC) is the second bridge constructed at the Second Narrows of Burrard Inlet in Vancouver, British Columbia, Canada. It is an essential transportation corridor along the Trans-Canada highway (Route 1), connecting the City of Vancouver to the District of North Vancouver, the City of North Vancouver, and West Vancouver. Recent evidence about potential earthquake sources, magnitudes and seismic activity in the area indicated the bridge would not withstand the design earthquake as per current code with the seismic design of the 1950's. The bridge was then retrofitted in 1994 by strengthening some elements and changing some of the original expansion and pin-bearings to isolation bearings.

The IMSNC is one of the bridges that will be instrumented under the SIMS project. As part of the instrumentation process a finite element model has been developed and updated using previously obtained ambient vibration measurements (Ventura et al., 2009, Turek, et al., 2010). The finite element model updating was done in two phases; the first to obtain a working stiffness value for a set of seismic isolation bearings installed in several locations on the bridge and the second to update several modes of a typical approach truss. The updated model will be used in fatigue and damage studies as a part of the monitoring system.

Description of the IMSNC

The Ironworkers Memorial Second Narrows Crossing is a 1292m-long composite structure. It carries six lanes of traffic (three lanes for each direction) and a 0.6m-diameter gas pipeline. The general configuration of the bridge and bent designation is illustrated in Figs. 6 and 7.

Figure 6. Overview of the IMSNC bridge in Vancouver.

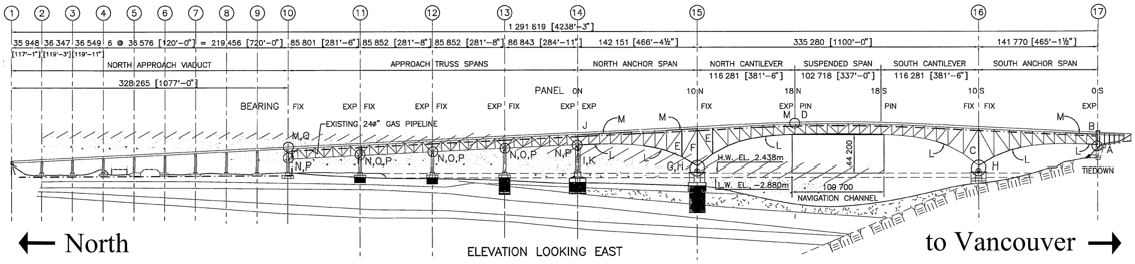
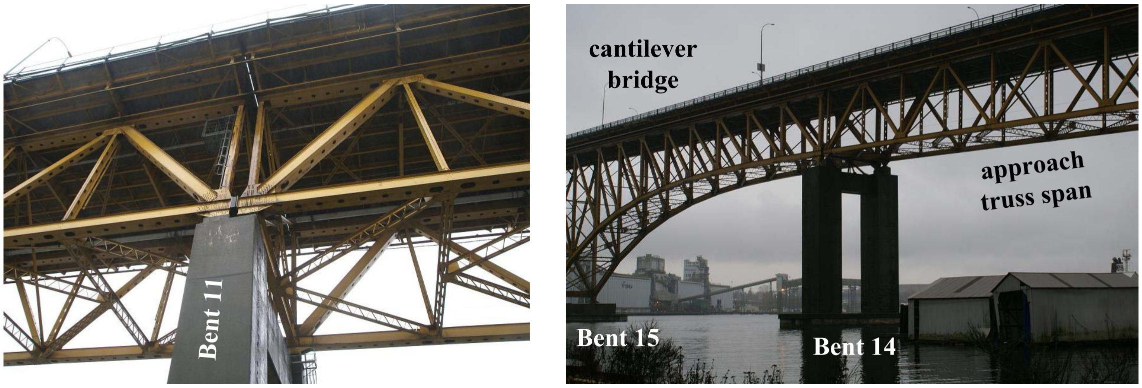


Figure 7: General configuration and bent designation of the IMSNC.

There are four 86.0m-long steel approach truss spans starting on the North shore of the crossing and extending out into the inlet. Each span has two 13.0m-depth custom steel warren trusses separated 14.6m apart. Both trusses are connected by horizontal and vertical bracing. The 0.2m-thick RC deck slab is supported on thirteen 0.8m-depth steel I-girders in the longitudinal direction and on a 1.7m-depth x 22.0m-long steel I-floor beam located transversally every 10.5m along the truss. The longitudinal girders are also connected transversally every 3.5m by a 0.5m-depth steel I-girders. The warren trusses are supported on isolation bearings protected with bumpers. The deck has transverse expansion joints at the ends of each span, so there is no structural continuity among them. The transition between two approaches and between the southernmost approach and the main cantilever section of the bridge is shown in Fig. 8.



a) Deck floor and steel warren trusses

b) Bent 14: south end of the approach truss spans

Figure 8. Approach truss spans.

Real-time seismic monitoring system

A real-time monitoring system (RTMS) is currently being installed on the IMSNC. The monitoring system will provide real-time information regarding structural performance and safety, primarily for seismic, but also applicable for a variety of load types. The monitoring system will be implemented in two phases: first to install the on-site hardware and second to implement a customized software and data processing system unique to the MoT/UBC network.

The general purpose of the system is to monitor the structural health of the bridge for seismic, impact and deterioration effects. This considers two loading levels: severe infrequent events, such as seismic and impact/collision; and frequent long-term effects, such as wind, traffic, etc. The system instrumentation will consist of:

- Vibration measurements utilizing uni- and tri- axial accelerometers
- Strong motion measurements off the structure, including free-field and down-hole accelerometers
- Strain measurements on the deck floor beams and major truss elements
- Temperature measurements at several locations, both the North and South ends
- Wind speed measurements at midspan

The data will be collected at a central data recorder, in which a certain amount of on-site data processing will occur. Then processed and raw data will be sent to UBC for further processing and storage. The monitoring system has approximately 100 channels; however due to the configuration of isolation bearings and expansion joints, the bridge is essentially split into 10 smaller independent structures. This means that in reality there is an average of about 10 channels per structure.

Summary and Conclusions

The technology to be implemented by the Ministry and UBC will be used to: i) detect, analyze and localize damage to structures; ii) transmit the data regarding these structures in real time via the internet; iii) display in animated and static web pages the data as appropriate for use by the Ministry and UBC. The alert systems and public access web pages will display real time seismic data from the BC Strong Motion Network to provide input for assessments by the Ministry of non-instrumented bridges. These systems may also provide other agencies, emergency responders and engineers with situational awareness.

Emerging technologies during the last decade allow us to monitor the "structural health" of any type of structures via the Internet. The research community has developed tools and algorithms that can be used now reliably to determine the state of health of a structure during its normal operating conditions and immediately after a significant event.

This Project will help transform the current practice of inspecting and evaluating all structures after an earthquake to a more rational and effective one that makes effective use of sensing technology with fast and efficient techniques for data analysis and interpretation. Inspections by the Ministry can then be focussed and prioritized to maximize the effectiveness of scarce resources.

Acknowledgments

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References

Turek, M., Ventura, C.E. and Dascotte, E., 2010. Model Updating of the Ironworkers Memorial Second Narrows Bridge, Vancouver, Canada, Procs of the *XXVIII International Modal Analysis Conference*, Jacksonville, Florida, Paper 257, 8 pages.

Ventura, C.E., Carvajal, J.C., Centeno, J., Pandey, B., 2009. Identification of modal properties of the Ironworkers Memorial Second Narrows Crossing: testing on deck. *Proc. 3rd International Operational Modal Analysis Conference – IOMAC*, Ancona, Italy