Seismic Structural Health Monitoring of Bridges in British Columbia, Canada

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SUMMARY:
The British Columbia Ministry of Transportation and the University of British Columbia have implemented a program to instrument key structures to provide confirmation of seismic capacity, assist in focusing retrofit efforts, perform structural health evaluations and provide rapid damage assessment of those structures following a seismic event. The instrumentation system installed at each structure will automatically process and upload data to a central server via the internet. The alert systems and public-access web pages can display real time seismic data from the structures and 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.

Keywords: Instrumentation, Real-Time Monitoring, Emergency Response

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

The MoT has been instrumenting structures in collaboration with the Earthquake Engineering Research Facility (EERF) at the University of British Columbia (UBC) since the late 1990's. The primary purpose of the original systems was to capture the ground motion input. More recently, the instrumentation has been expanded to incorporate Structural Health Monitoring (SHM). Two design-build bridges have included instrumentation; one existing bridge has also been instrumented, and up to eight more bridges will be added by the end of 2014.

In addition to the structural monitoring, the Geologic Survey of Canada (GSC) through the Pacific Geosciences Centre (PGC) maintains the Provincial Strong Motion Network (SMN) comprised of over 130 stations. As part of this network, the GSC developed a strong motion seismograph which is permanently connected to the Internet recording data continuously, rather than in "triggered mode".

The instrument also continuously computes a set of parameters which characterize the intensity of shaking and actively reports those values whenever ground shaking exceeds certain levels to the GSC's data centres. Over the last several years the MoT has been working with the PGC expanding the number of stations in the network.

Building on these collaborations, MoT and UBC embarked on a program called the British Columbia Smart Infrastructure Monitoring System (BCSIMS). The system integrates data from the instrumented structures and strong motion network, organizes and processes the information in an efficient manner, to deliver that information to the appropriate parties.

The Goals of the System are to: 1) Provide 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.

The implementation of the BCSIMS 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.

2. BCSIMS SYSTEM ARCHITECTURE

BCSIMS is a Supervisory Control and Data Acquisition (SCADA) system consisting of the following subsystems:

i. Public available and restricted web-based Graphical User Interfaces capable of displaying relevant information (web interface).
ii. One SIMS1 supervisory computer administrating the traffic between sensors, remote processing computers, remote users and data base.
iii. Remote SIMS2 processing computers connecting the on-site monitoring equipment to the system.
iv. One or more SIMS3 computers used for post-processing that may be more computationally intensive.
v. A Strong Motion Server to connect the SMN system to the database.

The key component of the system is the Global Database. This database contains all of the system data, analysis results, settings and other system information. As shown in Figure 1 the database communicates with the four other main components:

- Structural station: All processed and raw data, and settings are stored in the local database at the site; the local database will synchronize with the global database.
- Strong Motion Network: data is sent to the Global database via an interface server.
- Central software/Web information server: controls actions and communications to the database; in an event, calls upon additional resources such as the SIMS3 Advanced Analysis PC; when a web user requests data talks to the database.
- Administration module: a standalone software component for advanced/administrative users that allows for manipulation of most aspects of the system.

2.1. General Functionality

The local database at each structure contains all of the same fields as the global database, but only data for that structural station. This synchronization includes settings, results and raw data. Event triggers are set at the structural station in the hardware; a trigger initiates a recording that is placed in the local

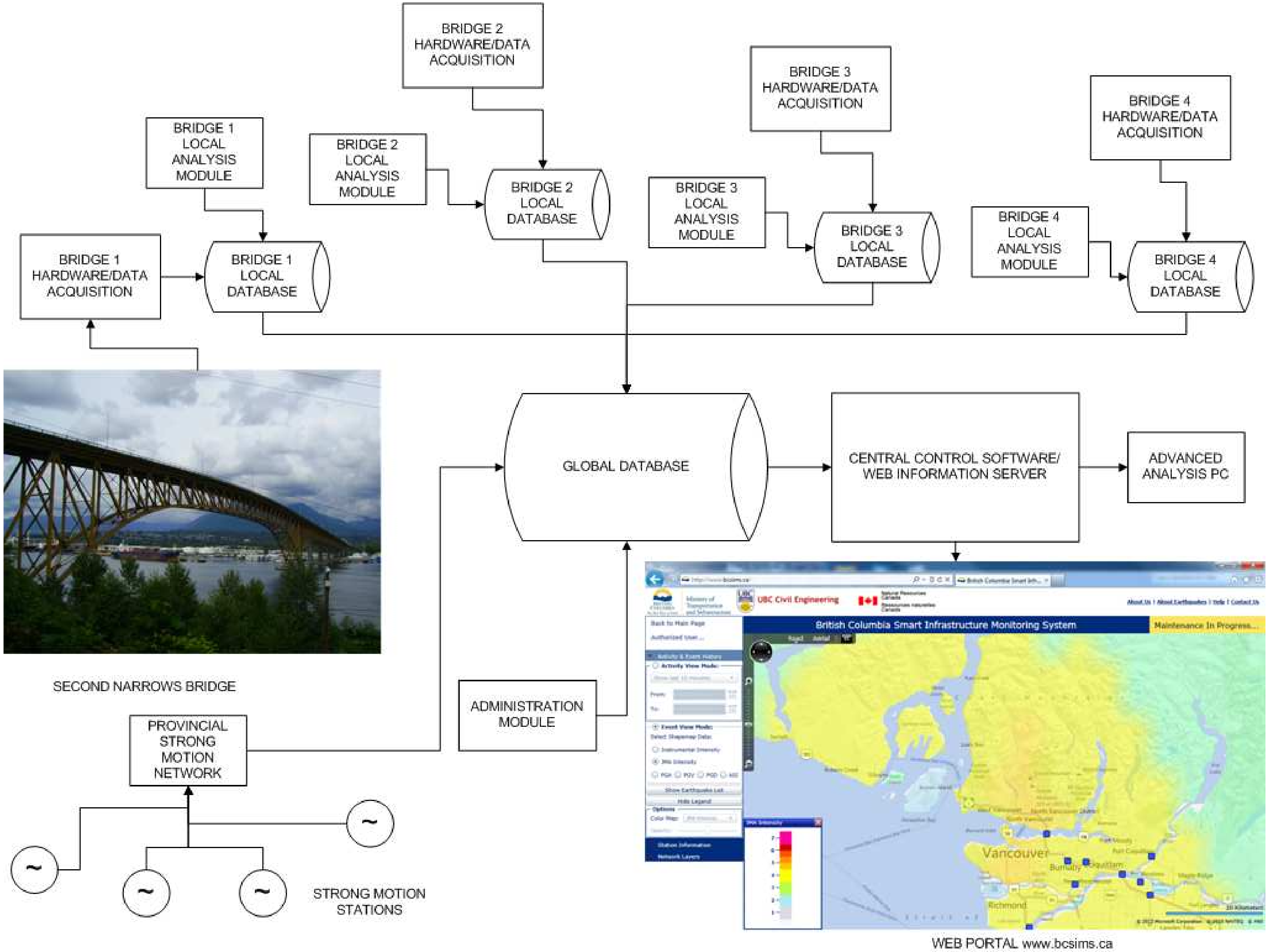

Figure1. BCSIMS System Architecture

database. This initiates the SIMS2 local analysis module; the results of the analysis are placed in the local database, and both raw data and results/parameters sync to the global database. Upon receipt of new data/results in the global database, the SIMS3 advanced analysis PC will initialize the report generator. Reports will be sent to the webpage and to selected user email accounts via HTML. The entire system will be run through the University of British Columbia with at least one backup server and PC's at the Pacific Geosciences Centre. In the future an additional out-of-province backup server will be setup.

2.2. Data Transfer

In order to streamline the data transmission process, UBC has developed its own standards and protocols. The merit of this approach is that it helps achieve consistency and platform-neutrality across all hardware platforms thereby simplifying the downstream processing. In addition to being able to use the most suitable hardware for a specific bridge (e.g. for technical performance or cost effectiveness), it also offers flexibility in replacing (e.g. defective) sensors in the future. Furthermore, it also significantly facilitates in assimilating the legacy stations.

The implementation of the data transfer protocol has been through one of two ways. A Windows COM interface is created that runs on the site PC next to the supplier software. This interface converts the data into the SIMS format and loads it directly to the local database for use in the BCSIMS system. The alternate approach is through a recently developed application called the 'Virtual Data Acquisition System' which also will run on the site PC and allows for upload of data in a variety of formats into a ring buffer which again loads data into the local database depending on the user request.

2.3. Control Centre

As a physical complement to the web based monitoring network a control room will be located at UBC. The Control Centre is envisioned as a situation-room with all the necessary skilled human resources plus enabling technologies available; and ensuring a continuous watch and attendance. Operational procedures will be enacted to regularly produce and syndicate to the sub-scribing stakeholders such as the MoT with sitreps (situation reports of what is happening) and progreps (progress reports relative to a goal which has been set). The Control Centre is housed in the Institute for Computing, Information and Cognitive Systems (ICICS).

2.4. Event Reports

Several event reports will be issued to various parties according to a predetermined subscriber list. Currently there will be three types of reports; they can be either automatically or manually generated depending on the type of report or event. The 'BCSIMS Quick Event Report' will provide a snapshot of a seismic event, including typical parameters such as location, magnitude, depth, etc. It will also list the top triggered ground motion stations, and a list of all of the structures in the network and a quick summary of their performance.

The second report is the 'BCSIMS Strong Motion Network Report' and it will contain all of the same information as the quick report but also include all of the ground motion stations and additional figures such as time histories and response spectra. The third report is the 'BCSIMS Structural Event Report'; it will provide information on the status and condition of the structure. Other details of the analysis from the various SIMS modules will be included. One report will be issued for each structure.

The Quick Report and SMN Report will be automatically issued when the strong motion network triggers; the Structures Report may trigger for several reasons, such as a seismic event, impact, traffic, wind or simply for a scheduled health assessment.

3. WEB INTERFACE

The BCSIMS.CA website is the gateway for user interaction and operational management. There are two view modes – public and restricted, which dictate the nature and amount of information accessible on the webpages. The public view consists of a shakemap intended for general public consumption and the restricted view contains further information for advanced users, such as downloadable data and unpublished results. Figure 2 shows a screen shot of the website homepage. The circles represent the strong motion network stations, and the squares are structural stations.

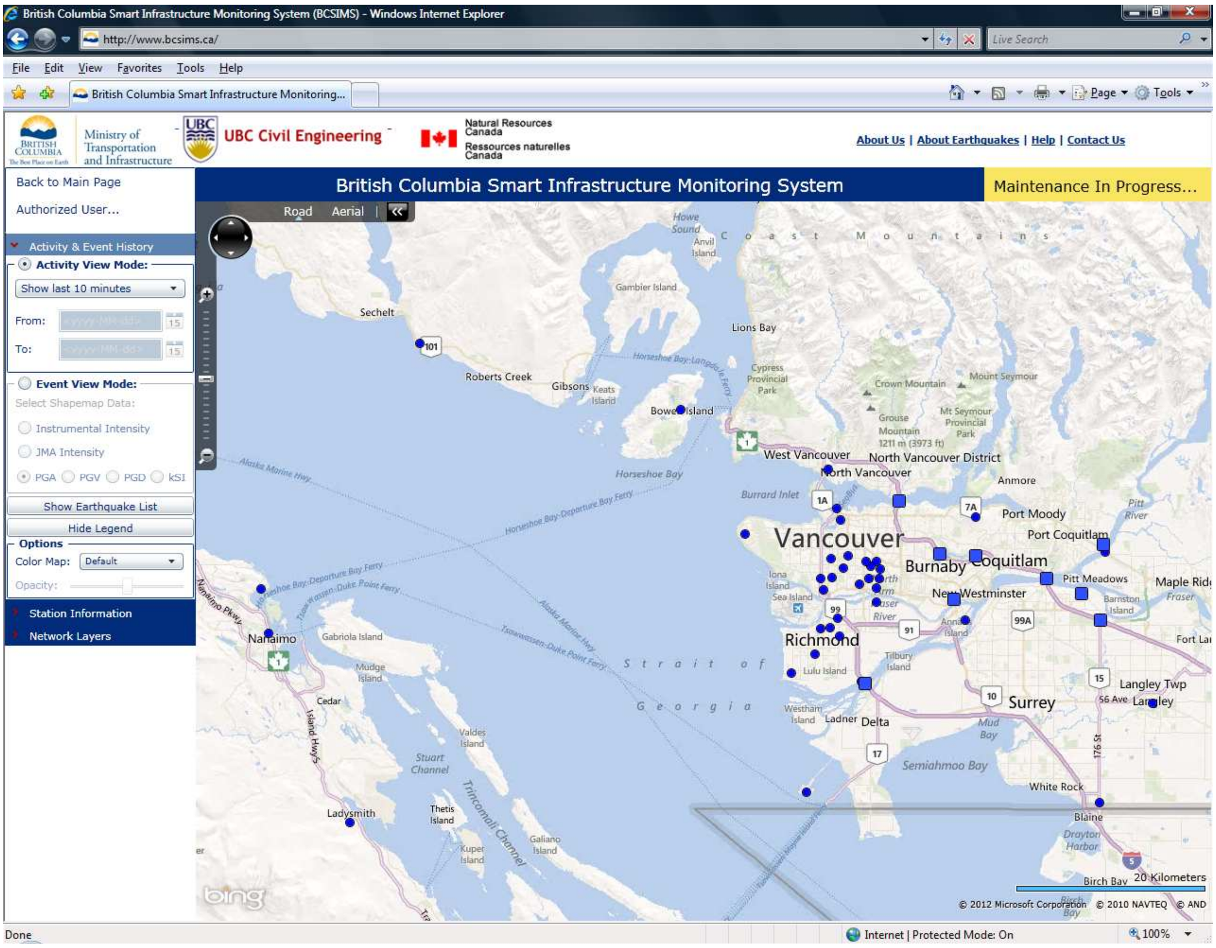

Figure 2. Screenshot of the BCSIMS homepage

The structure stations and strong motion sensors of the IANet are displayed as icons on a digital geomap. The interactive map allows zooming in/out and focusing on a particular station. Additional metadata for the structures such as location information and live links to webcams are also provided. Lists of recent events and recent seismic activities are provided from which the user can access published information for the corresponding events and activities.

In addition to the homepage and shakemaps, links from each bridge icon in the map directs to the Structures Information Pages. The idea of the Structures Information Page (SIP) is to provide an overview of the status of the structure and more detailed results of the various structural assessments carried out by the system. The SIP is divided into several tabbed sections. The tabs include a summary view, analysis view, data view and structure view. The exact configuration of the tabs is being finalized and may differ from this list; however the content is generally the same. The concept is to separate into information relating to events, data, analysis and static data such as instrumentation drawings and photos of the site. Figure 3 shows the current 'Activity View' (which contains data); a 3D model of the Pitt River Bridge is shown. The model can be used for various analysis results.

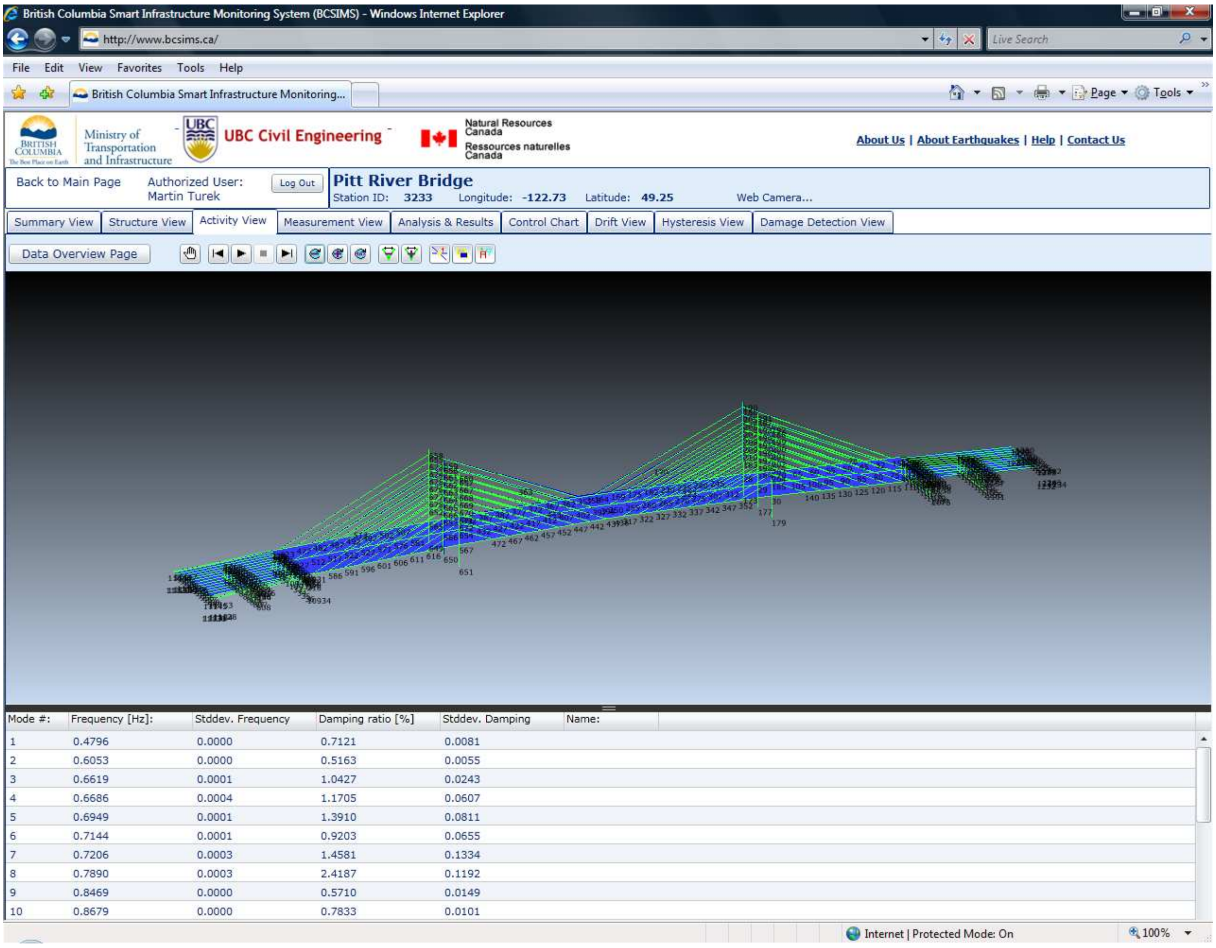

Figure 3. Structure Information Page 3D Model View

4. STRONG MOTION NETWORK

The provincial strong motion network (SMN) was developed and maintained by the Geologic Survey of Canada and the Pacific Geo-sciences Centre in Sidney, BC. A founding principle of the BCSIMS system is to incorporate the existing SMN into the network as a live map, which shows each station as a dot with acceleration and intensity. Additionally a shake map can be generated that is super-imposed on a map of the province; the user is able to zoom in and out with a mouse.

The current shake map capabilities of the system include Instrumental Intensity (Wald et al., 1999), Katayama Spectra Intensity (Katayama et al., 1998) and Japan Meteorological Agency Intensity (Karim and Yamazaki, 2002). KSI is generated by the SMN instruments and is sent to the database directly. The other parameters are computed at the SIMS3 PC; all of the maps are generated at the SIMS3 machine.

With respect to seismic monitoring in particular, complementary measurements from the GSC’s IANet are integrated into the BCSIMS systems. The input from IANet is vital in terms of sufficiency and robustness of the analysis.

5. STRUCTURAL MONITORING

The MoT has been instrumenting bridges and tunnels in collaboration with the University of British Columbia since the late 1990’s. Four structures were originally instrumented prior to the inception of the comprehensive BCSIMS scope. These include the French Creek Bridge and Portage Creek Bridge on Vancouver Island; George Massey Tunnel (Hwy 99) and Queensborough Bridge (Hwy 91A) both South of Vancouver. Two of these systems will be incorporated into the BCSIMS network by the end of summer 2012, with the other two coming online in the future.

In 2008 the new W.R. Bennett Bridge opened on Highway 97 near Kelowna, BC. The partially floating bridge was instrumented with a 12-channel accelerometer system. In 2009, the new Pitt River Bridge opened on Highway 7 near Maple Ridge, BC. The cable-stayed bridge was instrumented with a 46-channel system including accelerometers and wind. In 2011, instrumentation was installed on the 50-year old Ironworkers Memorial Second Narrows Bridge on Highway 1, between Vancouver and North Vancouver. The system features 122 channels of accelerometers, free-fields, downhole accelerometer, strain gauges, temperature and wind sensors.

Upcoming instrumentation includes the new Port Mann Bridge on Highway 1 between Coquitlam and Surrey, BC. The 10-lane cable-stayed bridge will be instrumented with 350 channels as part of the Port Mann Highway 1 improvement program. This major infrastructure project will also include instrumenting three underpass bridges, one 650 m long twin steel girder viaduct type structure, and seven more strong motion network stations. Another major infrastructure project in British Columbia, the South Fraser Perimeter Road, will introduce several more interchange structures and ground motion stations into the network.

5. DATA ANALYSIS

The BCSIMS network collects data from a variety of sources; similarly a variety of data analysis takes place at a variety of stages and locations. Data is analyzed at the structure by the supplier software, the SIMS2 module, or at the central location by the SIMS3 PC. All of the results are stored in the global database either directly as in SIMS3, or by the process of first storing in the local database, and synchronizing back to the global database.

5.1. Statistics

Statistics are generated at the site on all of the data channels, either by the supplier software or in the SIMS2 module. The SIMS2 module is capable of calculating the mean, RMS, max, min, peak, standard deviation and kurtosis. In some cases the supplier software will also generate statistics.

5.2. Ground Motion Analysis

The raw ground motion data is processed and stored in the COSMOS Strong Motion Data Format (COSMOS, 2001). This well-known data format creates three sets of files. Volume 1 files contain the raw data converted to physical units; these are typically referred to as the ‘uncorrected files’. Volume 2 files contain the products of the processed raw time history data from Volume 1. This includes correction for instrument response and digital filtering. The velocity and displacement are also obtained using numerical integration. Volume 3 files contain all of the spectral products, including the response spectra (absolute acceleration, relative velocity, relative displacement). Also included is the Fourier amplitude spectrum.

5.3. Modal Analysis

The SIMS2 module performs modal analysis on the acceleration time histories by means of the time domain Stochastic Subspace Identification technique as implemented in the ARTeMIS Extractor software (SVS, 2012). The output of the analysis provides the identified natural frequencies, mode shapes and damping ratio for a given dataset. These results are stored in the database and can be viewed on a 3D model of the structure through the web interface. The frequencies are posted on a Control Chart and can be tracked against time, depending on the frequency of scheduled measurements. The modes are also used in the model updating process.

5.4. Drift and Hysteresis Analysis

Functionality for drift analysis is setup in the SIMS2 module; the user specifies drift pairs and the system computes the drift from the integrated displacement values. The peak values during an event are stored in the database. The Hysteresis is simply the drift vs time plots.

5.5. Damage Detection

One of the major analysis groups in the BCSIMS system is using various techniques of damage detection. In addition to the techniques already implemented in the system, part of the mandate of the BCSIMS scope is to conduct research on new techniques and implementation of other existing techniques.

Several damage detection algorithms have been implemented into the BCSIMS network. The first is currently implemented in the SIMS2 module; the first is a statistical algrorithm (Balmes et al., 2008, Andersen et al., 2007). As with many algorithms, the method observes damage as changes to modal parameters. Consequently, the first requirement of the method is to obtain a series of data sets from the same structure, to obtain a baseline model from which to observe potential changes.

One desirable feature for this algorithm is its ability to detect damage even in the presence of noise, and common environmental effects such as temperature changes. An additional advantage is with regards to the concept of the sub-structuring or clustering of the model for the analysis. This is important for the speed of the algorithm, and for the accuracy of the damage identification. In addition, parts of the structure which are not expected to be damaged can be removed from the analysis to improve on speed and accuracy.

A second set of algorithms has been implemented to run in an offline mode through the SIMS3 machine. Five of those can be considered as mode shape based methods. These methods were compiled and used in a well-known study by Farrar and Jauregui (1998). These algorithms are:

- Damage index method – (Stubbs and Kim 1994)
- Mode shape curvature method – (Pandey, Biswas and Samman 1991)
- Change in flexibility method – (Pandey and Biswas 1994)
- Change in uniform load surface curvature – (Zhang and Aktan 1995)
- Change in stiffness method – (Zimmerman and Kaouk 1994)

The primary advantage of these methods is the relative ease of formulation, speed of use and simplicity of output results. However, the disadvantage is in the requirement for measurement of the mode shapes in more detail on the structure. This can present a problem in many situations when limited instrumentation is available.

The last set of methods is the flexibility-based methods, of which two are implemented also in an offline mode on SIMS3. The flexibility-based methods use the concept of changes in assembled flexibility matrix to identify and locate damage in a structure. The flexibility matrix can be obtained for stochastic (output-only) data by manipulations of the results from time domain system identification. Previous work by Turek (2007) utilized two variations of stochastic flexibility methods. These methods are:

- Stochastic Damage Locating Vector (SDLV) Technique - (Bernal, 2006), based on the Damage Locating Vector (DLV) Technique - Zonta and Bernal (2006), Bernal (2002).
- Proportional Flexibility Matrix Technique - (Duan et al., 2005)

5.6. Finite Element Analysis

Finite element models of the monitored structure are another important element in the overall data analysis capabilities. Software is setup on the SIMS3 for the analysis; both during initial calibration and during routine and triggered events. The models will be updated using data from the measured structure, and are used for analysis such as:

i. Stress and load
ii. Fatigue
iii. Damage location and quantification
iv. Prognosis (life expectancy)

For most monitoring system cases, a preliminary FEM will be created and an on-site ambient vibration test will be performed. The FEM will then be manually or automatically updated based on the obtained results. The model can then be used to:

i. Design the permanent monitoring system
ii. Evaluate potential damage detection methods through simulation
iii. Perform real-time analysis
iv. Be used for scheduled structural analysis based on updated models

5.7. Finite Element Model Updating

Automated FEM updating is performed through the SIMS3 PC using the FEMTools (DDS, 2012) commercially available software. Once a new set of modes is placed in the database, an automated process on the SIMS3 machine triggers an updating run using the software; the updated modal comparison matrix and parameter changes are placed in the database. The new FE model is placed in a folder labelled with the event ID and time. The new updated model can be used for further analysis. The process requires a preliminary manual updating of the model, usually done with data from a more detailed ambient vibration test. The settings from this 'manual' update are used to create command files for the automated process.

6. SUMMARY AND FUTURE WORK

The British Columbia Ministry of Transportation and the University of British Columbia have embarked on a program which is called the British Columbia Smart Infrastructure Monitoring System (BCSIMS). The system aims to integrate data from the instrumented structures and the strong motion network, organize and process the information in an efficient manner, and to deliver that information to the appropriate parties.

The Goals of the System are to: 1) Provide 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. Currently the system incorporates more than 130 strong motion network stations, five structural stations, and as many as ten more structural stations by the end of 2014.

The system is based on local database and analysis modules, located at every structural monitoring site. A global database, web server and advanced analysis PC are located at the University of British Columbia and act as the heart of the system. Access for most users is via the website BCSIMS.ca which allows for viewing of the strong motion network, structural stations, data, results and event reports.

The next phase of development of the BCSIMS system will be through the European Union funded ISMS Project. This will feature development and implementation of new damage detection algorithms. It will also feature several upgrades to the existing BCSIMS framework such as more sophisticated graphical interfaces, expansion and revision of the current database functionality and more efficient analysis methods.

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