Structural health monitoring network in British Columbia, Canada

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Abstract
This paper presents a structural health monitoring (SHM) network in British Columbia (BC), Canada that involves 14 bridges, 1 tunnel and 12 public schools. The SHM system is part of a province-wide monitoring network, the British Columbia Smart Infrastructure Monitoring System (BCSIMS). The SHM network automatically retrieves structural vibration data from these instrumented structures on a regular basis and makes them available to download on the BCSIMS website (www.bcsims.ca). The collected data is then automatically analysed and permanently stored in a data centre located at the University of British Columbia. The objective of the SHM network is to provide the ministry with information on the performance of instrumented structures following a significant event such as a strong earthquake or powerful wind. Such information is then used to assess the structural safety and health state of these structures to help and support the inspection and maintenance program. The SHM network is designed to automatically issue structural reports within 15 minutes following a significant earthquake. The entire system has been tested and validated by an earthquake which occurred on December 29th, 2015 on Sidney Island, BC. The SHM system responded to the earthquake as it was designed to do, and provided the required information that the engineers needed to make immediate decisions and respond to the emergencies in an efficient manner.

Key words: Structural health monitoring, real-time data processing, modal analysis and testing, earthquake reports

1. Introduction

The southwest coast of British Columbia (BC) is located over an active subduction zone, which is one of the most seismically active fault zones in Canada. This subduction zone can generate earthquakes with magnitudes of up to 9.0, therefore creating seismic hazards to BC and risks to the civil engineering structures built on those areas.

To help mitigate this risk, the BC Ministry of Transportation and Infrastructure (MoT) together with the Geological Survey of Canada (GSC) have been maintaining an urban strong motion network of over 160 acceleration sensors. These instruments have been deployed to monitor and report the seismic activities in BC. The MoT is responsible for 400 km of provincial disaster response routes and maintains over 2,500 bridges in BC. Many of these bridges are located in the highest seismic zones and are vulnerable to extensive damage in even a moderate quake and potential collapse in a major earthquake. By identifying MoT structures and facilities most susceptible to seismic
forces through automatically generated shakemaps, decision-makers can effectively handle risk management. Fast and accurate field intelligence immediately following an earthquake can ensure the most effective deployment of vital services and mitigate damage to the built environment.

The Ministry of Transportation has been instrumenting tunnels and bridges in a collaborative effort with the Earthquake Engineering Research Facility (EERF) at the University of British Columbia (UBC) since the late 1990s. The primary purpose of most systems was to monitor the ground motion input and its effect on structures during strong shaking. The MoT and UBC started a program called the British Columbia Smart Infrastructure Monitoring System (BCSIMS), which integrates data from the instrumented structures (currently 27 in total) and the strong motion network. The BCSIMS program also incorporates a comprehensive structural health monitoring (SHM) system, which processes and delivers results and related reports in real-time to predefined recipients, such as bridge inspectors at the MoT. Consequently, the system is also able to provide immediate notifications after an earthquake event. The goals of the system are: (i) to provide a real-time seismic structural response system to enable rapid deployment and prioritized inspections of the MoT’s structures; (ii) to develop and implement a structural health monitoring program to address the need for safe and cost-effective operation of structures in BC; and (iii) to provide a real-time working platform (www.bcsims.ca) that can integrate many aspects of seismicity in BC (1).

It is very common to see a large number of slight-to-moderately damaged bridges, along with the heavily damaged or undamaged structures following a large earthquake. Detailed bridge inspection of these damaged structures takes a lot of time to decide if the damage is structural and if it is safe to reoccupy the bridge. The SHM systems in the BCSIMS network provide the means to help make such decisions faster and with more confidence. In other words, the implementation of the BCSIMS transforms the current practice of inspecting and evaluating all structures after an earthquake to a more rational and practical one that makes effective use of state-of-the-art sensing technology.

2. Architecture of Structural Health Monitoring System

The BCSIMS homepage shows a map of the province of British Columbia; it includes major fault lines around BC and several structural layers such as bridges, schools, and tunnels. The screenshot in Figure 1 illustrates the concept and showcases the BCSIMS bridge layer. For completeness, all structures that are monitored in real-time are listed in the subsequent tables, Table 1 and Table 2. The monitoring data of each instrumented structure can be accessed by a central server via the internet. The types and the number of sensors installed on each structure depend on the dynamic characteristics of each individual structure, as well as the objective of the seismic SHM system installed.

2.1 Data Acquisition and Storage

2.1.1 Raw Data Archiving

The monitoring data from each structure is collected in real-time and archived in a ring buffer on data recorders located in the local field. The collected data is then transferred and stored in the BCSIMS VIF file format in the UBC data centre. The VIF files are
developed to streamline the data transmission process and unify the proprietary data formats of different hardware suppliers. It contains raw data from all of the sensors for each monitored structure, including mechanical quantities or other relevant environmental and operational variables (EOVs) such as displacement, velocities and acceleration data, as well as weather data (temperature, humidity, wind speed, wind direction, etc.) and operational loads on the structure. The raw VIF data files in the data centre are compressed to minimize the disk space. The compressed data is then stored in a ring buffer whose length is scalable based on the available disk space on the server.

![Figure 1: BCSIMS homepage (www.bcsims.ca) with bridge layer applied](image)

**Table 1: List of instrumented structures in the SHM network (BCSIMS)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Structure name</th>
<th>Total length</th>
<th>Year instrumented</th>
<th>No of channels</th>
<th>Type of sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>French Creek (FC)</td>
<td>200 m</td>
<td>1997</td>
<td>12</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>George Massey Tunnel (GMT)</td>
<td>660 m</td>
<td>1996</td>
<td>11</td>
<td>A P</td>
</tr>
<tr>
<td>3</td>
<td>Queensborough Bridge (QB)</td>
<td>914 m</td>
<td>1996</td>
<td>12</td>
<td>A P</td>
</tr>
<tr>
<td>4</td>
<td>Ironworkers Memorial Second Narrows Crossing (IMSNC)</td>
<td>1,290 m</td>
<td>2011</td>
<td>122</td>
<td>A S W T</td>
</tr>
<tr>
<td>5</td>
<td>Pitt River Bridge (PR)</td>
<td>380 m</td>
<td>2009</td>
<td>46</td>
<td>A W</td>
</tr>
<tr>
<td>6</td>
<td>William R. Bennett Bridge (WRB)</td>
<td>1,077 m</td>
<td>2008</td>
<td>12</td>
<td>A</td>
</tr>
<tr>
<td>7</td>
<td>Portage Creek Bridge (PCB)</td>
<td>129 m</td>
<td>1983</td>
<td>41</td>
<td>A S</td>
</tr>
<tr>
<td>8</td>
<td>Port Mann Bridge (PM)</td>
<td>850 m</td>
<td>2013</td>
<td>336</td>
<td>A W D T H P</td>
</tr>
<tr>
<td>9</td>
<td>176th Underpass (176B)</td>
<td>75 m</td>
<td>2013</td>
<td>26</td>
<td>A T H</td>
</tr>
<tr>
<td>10</td>
<td>Gaglardi Way Underpass (GWU)</td>
<td>65 m</td>
<td>2013</td>
<td>22</td>
<td>A T H</td>
</tr>
<tr>
<td>11</td>
<td>Kensington Avenue Underpass (KAU)</td>
<td>75 m</td>
<td>2013</td>
<td>30</td>
<td>A T H</td>
</tr>
<tr>
<td>12</td>
<td>Fraser Heights - Wetlands (FHW)</td>
<td>476 m</td>
<td>2013</td>
<td>20</td>
<td>A T H</td>
</tr>
<tr>
<td>13</td>
<td>BNSP Sunbury Bridge</td>
<td>68 m</td>
<td>2014</td>
<td>36</td>
<td>A H W D</td>
</tr>
<tr>
<td>14</td>
<td>BNSF Viaduct East Mill Access</td>
<td>195 m</td>
<td>2014</td>
<td>84</td>
<td>A H W D</td>
</tr>
<tr>
<td>15</td>
<td>Hwy-17 Deltaport Bridge</td>
<td>133 m</td>
<td>2014</td>
<td>36</td>
<td>A H W D</td>
</tr>
<tr>
<td>16</td>
<td>Earthquake Engineering Research Facility (EERF) at UBC</td>
<td>-</td>
<td>2013</td>
<td>16</td>
<td>A</td>
</tr>
</tbody>
</table>
Table 2: List of instrumented schools in the SHM network (BCSIMS)

<table>
<thead>
<tr>
<th>No.</th>
<th>School name</th>
<th>District</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>South Delta</td>
<td>Delta, BC</td>
</tr>
<tr>
<td>3</td>
<td>Phoenix</td>
<td>Campbell River, BC</td>
</tr>
<tr>
<td>4</td>
<td>Henderson</td>
<td>Powell River, BC</td>
</tr>
<tr>
<td>5</td>
<td>Wellington</td>
<td>Nanaimo, BC</td>
</tr>
<tr>
<td>7</td>
<td>Matsqui Elementary</td>
<td>Abbotsford, BC</td>
</tr>
<tr>
<td>8</td>
<td>Aberdeen Elementary</td>
<td>Abbotsford, BC</td>
</tr>
<tr>
<td>11</td>
<td>Burnaby Central</td>
<td>Burnaby, BC</td>
</tr>
<tr>
<td>12</td>
<td>Parkland Secondary</td>
<td>Saanich, BC</td>
</tr>
<tr>
<td>13</td>
<td>Cordova Bay Elementary</td>
<td>Saanich, BC</td>
</tr>
<tr>
<td>14</td>
<td>Quadra</td>
<td>Victoria, BC</td>
</tr>
<tr>
<td>15</td>
<td>Strathcona</td>
<td>Vancouver, BC</td>
</tr>
</tbody>
</table>

2.1.2 Long-term Statistics

The archived raw data is analysed in real-time and stored permanently in the data centre. The analysis is done for each channel on each structure, and it includes basic signal statistics such as maximum and minimum values, as well as mean, standard deviation, skewness, and kurtosis, see Eq. (1) - (4). This analysis is done for each measured quantity, including environmental parameters. Tracking the basic statistical values is important because many damage detection and localization algorithms require the environmental variables as inputs. Thus, the algorithms can be developed and trained to discriminate between normal fluctuation in the system response and structural anomalies, such as damage (2, 3).

\[
\text{Mean} [X] = E[(X - \mu)]
\]  
\[
\text{Var} [X] = E[(X - \mu)^2]
\]  
\[
\text{Skew} [X] = E\left[\frac{(X-\mu)}{\sigma}\right]^3
\]  
\[
\text{Kurt} [X] = E\left[\frac{(X-\mu)}{\sigma}\right]^4
\]

2.1.3 Other Measurements

A certain amount of raw data from each structure is permanently stored on the data processing server every day. The collection of such data from each structure is called “scheduled measurement”, and it is used to test the new tools and techniques that are being continuously developed as part of the BCSIMS project. The current emphasis is on developing damage detection and localizations tools. The special events data, on the other hand, includes earthquake data or other damaging incidents such as ship collision, strong wind or vibration data for any other abnormal events. This includes invasive restoration and maintenance where parts of the structure are exchanged or added during regular maintenance; for example, stay cables may be replaced, and asphalt has to be renewed in regular intervals. The purpose of storing data from such events is to create a collection of pseudo-damage scenarios, which can then be used for research purposes.
### 2.2 Data Interpretation

#### 2.2.1 Drift Analysis Results

One of the decisive control parameters for damage in seismic design is drift, and it is monitored continuously for many structures in the SHM network. Drift can be evaluated for bridge piers, bridge towers, or building columns. It is defined as the relative displacement of the column top with respect to its base, and it is strongly controlled by the displacement demand. To calculate the drift, the displacements at these two locations need to be measured at the top and the base of the column. It is possible to calculate displacements from acceleration data by integrating over the recorded accelerations twice. However, the integration operation on raw data significantly increases the noise amplitudes in the integrated signal and can lead to misleading results (4). Several tools have been developed in the BCSIMS to minimize such noise increase: the response of a bridge pier at resonant frequency has much higher signal-to-noise ratio; therefore, the noise influence during the integration and differentiation is minimal. Any drift value exceeding a predefined threshold value may be indicative of possible damage in the structure. The drift thresholds for each pier have been determined based on the Canadian Highway Bridge Design Code requirements, and results from detailed nonlinear finite element model analyses.

#### 2.2.2 Tracking of Modal Identification Results

Dynamic modal properties of the structure (e.g., modal frequencies, modal damping ratios, and mode shapes) are calculated and continuously monitored in real-time using the stochastic subspace identification (SSI) method, principal component (5, 6). The method is combined with a hierarchical clustering approach for automated mode selection. The algorithm is semi-automated, because two structure-specific parameters have to be set a-priori, i.e., the minimal distance of adjacent modal frequencies and the number of most dominant modes. The mode tracking is done through a static mode tracking procedure that compares both frequency and mode shapes (7); however, no human interaction is required in this process. The measurement duration $T$ is structure specific, and it is determined based on the rule of thumb: $T = 1000 T_1$, with $T_1$ being the first fundamental period of the structure. The resulting modal parameters are stored permanently on the server both for long-term and short-term analyses.

### 2.3 Structural Event Report

As soon as an earthquake with characteristics (see section 2.4) are registered with the BCSIMS network, the SHM network automatically initiates an event recording for each instrumented structure, and it is permanently stored on the server. The structural event report, which is issued approximately 15 minutes after the seismic event is over, will be automatically generated and e-mailed to a predefined subscribers list, and will then be published on the BCSIMS website. This report provides key information on the status of each bridge after an earthquake. The recorded vibration amplitudes on the bridge are automatically compared with user selectable thresholds in the report. Any recorded value that exceeds these thresholds is clearly indicated in the report by graphs and figures, and recommendations are also given in the report in regard to the actions to be taken. This event report may also be issued for several reasons in addition to seismic...
events, such as impact, over loading, wind, ship collision with a bridge, or simply for a scheduled health assessment of the structure.

3. **Case Study 1: System Response to the M4.8 Earthquake on Sidney Island in 2015 in BC, Canada**

A seismic event, which occurred in BC, is used as an illustration of how the SHM network performs. An earthquake with a magnitude of 4.8 (USGS) occurred near Sidney Island in BC (48.6038 latitude and −123.3068 longitude) on Wednesday December 30th, 2015 at 07:39 AM UTC. Fifty strong motion stations were triggered due to this shaking, and the earthquake was felt across the Lower Mainland of BC. The locations of the triggered stations are depicted in Figure 2, and the maximum horizontal acceleration of 0.04 g was recorded at the Brentwood Bay station on Vancouver Island, which is 11.47 km away from the epicentre of the earthquake. Since the magnitude of this earthquake was bigger than 3, more than one internet accelerometer (IA) station was triggered, and the epicentre of the earthquake was less than 200 km from the nearest IA station, the BCSIMS system automatically registered this earthquake on the server, and the SHM network automatically initiated a collection of earthquake event data from each instrumented structure after the earthquake was over. Collected earthquake event data was then automatically analysed, and one structural event report was produced for each structure. The entire process was completed within 15 to 20 minutes following the earthquake, and no human interaction was needed.

![Figure 2: Automatically generated shake map for the M4.8 Sidney Island earthquake in BC. The location of the epicentre is indicated by a red star. A total of 50 earthquake stations were triggered, which are marked by green circles (www.bcsims.ca).](image-url)
4. Case Study 2: Port Mann Bridge

4.1 Bridge Description

With a total length of 2,020 meters and a width of 65 m (10 traffic lanes), the Port Mann Bridge spans the Fraser River and connects the two cities of Surrey and Coquitlam in BC, Canada. Constructed in 2012, the bridge is divided into three sections: an 850m-long cable-stay and two approach viaducts. The deck structure consists of steel girders and transverse floor beams, which support precast concrete deck panels. The entire cable stay is also divided into two separate decks, which are connected by median struts, as shown in Figure 3 (d). In total, there are 288 cables installed to connect two 163 meter tall piers to the deck. Each cable has its own properties that vary from one another. The north and south approaches, on the other hand, consist of three concrete box girder sections. On many of the approach piers there are viscous dampers installed to prevent excessive longitudinal movement. The foundations for each of the piers consist of steel piles with diameters of 1.8 m with reinforced concrete.

Figure 3: Port Mann Bridge. (a) View from North, (b) cross section of approach viaducts, (c) dampers at approach piers, (d) median struts connecting the East and West deck (Google)

4.2 Instrumentation

The Port Mann Bridge instrumentation includes a total of 340 measurement channels including displacement transducers at the expansion joints, vibration sensors, and further sensors to record environmental and operational variables. The instrumentation is primarily meant to record structural vibrations under strong motions, and to study the combined effects of the soil and the structure. The instrumentation is distributed across
the entire structure, including boreholes, foundations, approach viaducts, and the cable stay.

Figure 4: Instrumentation map for Port Mann Bridge (deck, towers and foundation only)

The cable-supported part of the Port Mann Bridge is instrumented through 34 acceleration sensors (70 channels in different directions), 12 displacement transducers, and 2 weather stations, Figure 4. Weather stations are located at the top of each tower and measure the temperature and humidity, as well as the wind speed and its direction, which sums up to 8 channels per station. The displacement transducers are located at the expansion joints at either side of the cable stay to measure the displacement due to temperature variations, traffic, and external loads. A toll station at the south end of the bridge records both the number and length of vehicles crossing the bridge.

4.3 Modal Identification Results

The modal analysis results of the Port Mann Bridge have been validated in comparison to the modal parameters obtained through reference-based field measurements\(^1\) (9). The first eight documented modes of vibration were estimated accurately, and a ninth physical mode has been identified, but is not always excited sufficiently through ambient excitations, see Mode 6 in Figure 5. The fundamental frequency of the bridge is 0.233 Hz (natural period 4.29 sec), and the maximum deviation from the target values does not exceed 0.24% for all considered modes of vibration.

4.4 Environmental and Operational Variables

The environmental and operational variables influence the vibration behaviour of bridges significantly, (10, 11). The fundamental frequencies of the Port Mann Bridge are not particularly sensitive to anomalies in the system response, which is due to the

\(^1\) Target values have been created in ARTeMIS (8)
large wave lengths of the corresponding modes of vibration. However, they can be used to show the correlation of the dynamic behaviour and EOVs, such as the ambient temperature and mean vibration level. It is observed that the fifth natural mode of the main span is the most sensitive mode to fluctuations in temperature, see Figure 6. Fitting a linear line between temperature and modal frequency revealed that the fifth modal frequency decreased by about 18 mHz when the temperature drops from 32°C to -5°C. A very similar trend can be observed for the average acceleration level. The mean vibration level has shown to be a good indicator for the operational loads \( \Delta m \) on the bridge (12), and increased operational modes appear to result in lower natural frequencies. For Mode 5, load-induced fluctuations amount up to 19 mHz.

![Figure 5: Port Mann Bridge. (a) Control chart for the first nine modal frequencies, and (b) corresponding mode shapes.](image)

4.5 Discussion

The SHM network has delivered very reliable data for both the vibration behaviour of the bridge and the environmental information. The weather data has been cross-checked with nearby weather stations. The vibration data yields modal parameters that are very close to those estimated from reference-based field measurements. Moreover, the modes of vibration are very consistent over a period of six months. Fluctuation in modal parameters could be attributed to the change in environmental conditions. The traffic volume on the bridge, on the other hand, showed weak correlation with the change in modal frequencies because only the number of vehicles crossing the bridge is recorded on the traffic volume data, and the traffic congestions are misinterpreted, as the largest
vehicle loads on the bridge occurs when the traffic is not moving. To improve the SHM system on the bridge, a bridge weight in motion monitoring system could be considered.

![Figure 6: Correlation analysis. Dependency between the fifth natural frequencies and both temperature and mean vibration level.](image)

5. Conclusion

Since 2009, a comprehensive SHM network has been designed, installed, and maintained by UBC for the BC MoT bridges. The network is part of a province-wide seismic monitoring system, the BCSIMS. The SHM network collects raw monitoring data from all instrumented structures, and monitors the structural health state in real-time by evaluating drift values and modal parameters. The earthquake which occurred on Sidney Island, BC on Wednesday December 30th, 2015 has proved that the SHM network could react to the earthquake and produce structural event reports approximately 15 minutes following the earthquake. The SHM data collected from the Port Mann Bridge over the past six months has been used in this paper to showcase the SHM tools and methods developed.

Acknowledgements

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References