British Columbia Smart Infrastructure Monitoring System

Yavuz Kaya, Carlos Ventura, Martin Turek, Sharlie Huffman

BRITISH COLUMBIA SMART INFRASTRUCTURE MONITORING SYSTEM

Yavuz Kaya[1], Carlos Ventura[1], Martin Turek[1], Sharlie Huffman[2]

[1]*The University of British Columbia, Vancouver, 6250 East Mall, V6T1Z4, Canada*
[2]*British Columbia Ministry of Transportation, Victoria, BC, Canada*

kayaya@mail.ubc.ca

ABSTRACT

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 : *Real-Time Monitoring, Emergency Response, Damage Deteaction, Modal Identification*

1 INTRODUCTION

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 west coast of BC lies in Canada's highest seismic zone, a as a result, the primary purpose of these original systems was to capture the ground motion input in the event of an earthquake. 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 to system 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 ground monitoring stations. 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.

2 BCSIMS SYSTEM ARCHITECTURE

Figure 1 presents an overview of the BCSIMS system architecture. The system combines components of hardware and data acquisition, data storage and processing, and network communication. As shown in the Figure, structural data is acquired on a local level, using as an example the Second Narrows Bridge (a total of four generic structural stations are shown, but an indefinite number of stations can be added to the system). The raw data from the local DAQ is sent to a local database, which contains all of the same fields as the global database. Event triggers are set at the structural station in the hardware; a trigger initiates a recording that is placed in the local 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 a report generator. Reports will be sent to the webpage and to selected user email accounts via HTML.

In order to streamline the data transmission process, UBC has developed its own data archiving standards and protocols. The advantage 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.

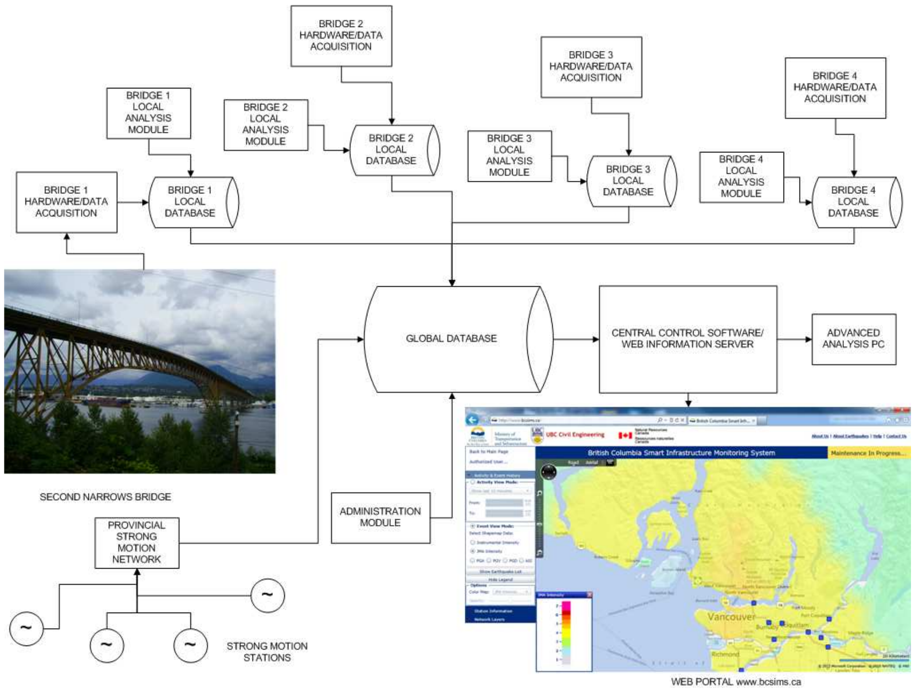

Figure 1: BCSIMS System Architecture:

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 uploads it directly to the local database for use in the BCSIMS system. The second approach is through an application called the ‘Virtual Data Acquisition System’, VDAS, which will also run on the site PC. Since typically each hardware supplier has its own data format, VDAS is designed in such a way that it can read different data formats, converts them to SIMS format, and uploads them into a ring buffer in local database.

3 WEB INTERFACE

The www.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 processed and/or raw downloadable data and unpublished results. Fig.2 shows a screen shot of the website homepage. The circles represent the strong motion network stations, and the squares are structural stations.

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.

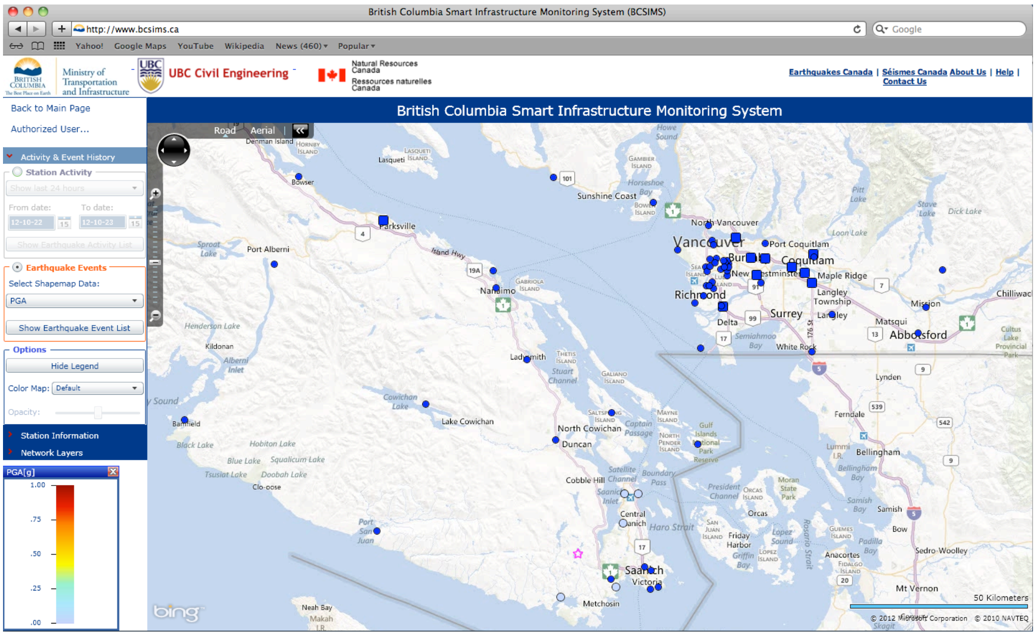

Figure 2: Screenshot of the BCSIMS homepage

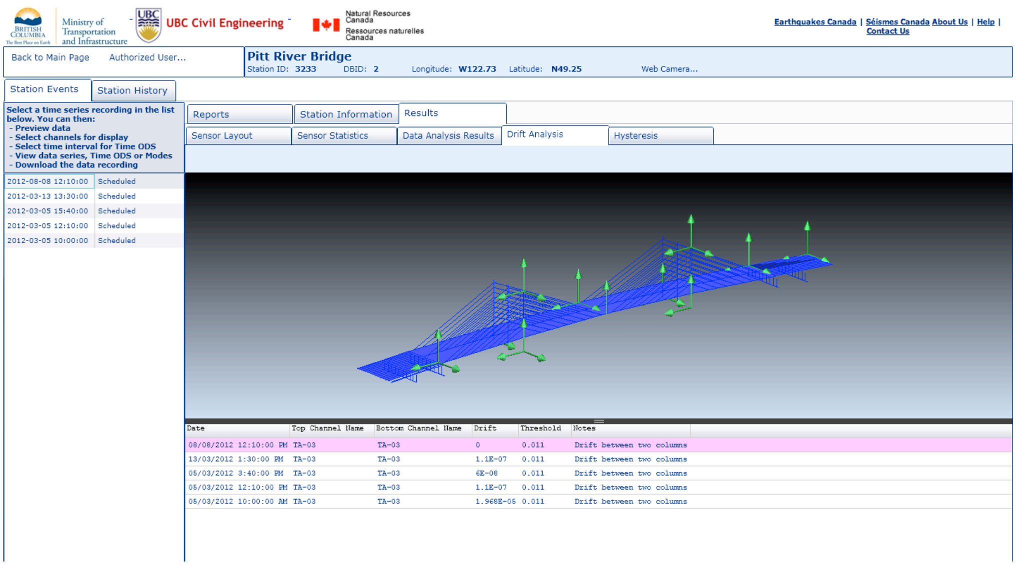

Figure 3: Structure Information Page 3D Model View

There are two main view modes in the main page of the bcsims.ca from which the user can extract information: Station Activity & Event view mode and Earthquake Events view mode. Station Activity & Event mode displays activities recorded for each IANet station within a user selectable time period. Recorded activities are indicated by color and circle. Size of the circle indicate the maximum measured amplitude of the record (PGA), where as color depicts the kSI (Katayama Spectral Intensity) value. By clicking on any of the IANet station on the geomap, the user can access all the activities recorded by that station, and download raw or process data such as velocity, displacement, Fourier amplitude spectrum, and response spectrum. Earthquake Event View mode, on the other hand, displays recent earthquakes that has happened in BC with its epicenter located on geomap. The epicenter of an earthquake is revealed by a colored-star where the size of star indicates the moment magnitude of the earthquake. The user has the option to display several different shake maps such as Instrumental Intensity [1], Katayama Spectra Intensity [2], and Japan Meteorological Agency Intensity [3]. Other options include the, PGA, PGV and PGD values. The default option is the PGA shake map.

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. Fig.3 shows the current 'Drift Analysis' (which contains data); a 3D model of the Pitt River Bridge is shown. The model can be used for various analysis results.

4 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. 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. Work is underway to bring these legacy systems online into the BCSIMS network. These bridges typically featured strong-motion type accelerometers, in downhole, on footings and on the structure. There are also some downhole piezometers (measuring pore pressure) and strain gauges (measuring strain on glass-fiber column wraps).

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 sensor. In 2011, instrumentation was installed on the 50-year old Ironworkers Memorial Second Narrows Crossing Bridge on Highway 1, between Vancouver and North Vancouver. The system features 122 channels of accelerometers, free-fields, downhole accelerometer, strain gauges, and temperature and wind sensors. Pitt River and Second Narrows were the first two bridges to be implemented into BCSIMS.

Upcoming instrumentation includes the new Port Mann Bridge (Figure 4) on Highway 1 between Coquitlam and Surrey, BC. The 10-lane cable-stayed bridge will be instrumented with cable and structure accelerometers, wind, temperature and humidity sensors, as well as ground and downhole stations. This is a part of a major infrastructure project that will also include instrumentation on three underpass bridges, one 650 m long twin steel girder viaduct type structure, and seven more strong motion network stations. All of these systems will be implemented to the BCSIMS network.

Figure 4: Port Mann Bridge

5 DATA ANALYSIS

Data analysis is a core functionality of the BCSIMS system. Acknowledging the high cost and risk associated with continuous data-streaming, founding philosophies of the system is to process data at the site and transmit results in real time only; sending full data only as the connection/bandwidth is available.

As shown in Figure 1, the data analysis takes place at a variety of stages and locations. Data is analyzed at the structure site by the SIMS2 module and at the central site by the SIMS3 PC. Post processing of data includes statistics, ground motion analysis, modal analysis, drift and hysteresis analysis, damage detection, finite element analysis, and finite element model updating. All of these results are stored in the global database either directly by SIMS3, or by the process of first storing in the local database, and synchronizing back to the global database by SIMS2 module.

Statistics are generated at the structure site on all of the data channelsby the SIMS2 module. It is capable of calculating the mean, RMS, max, min, peak, standard deviation, skewness, and kurtosis. Such statistical values help to better understand the structural behavior under different loading conditions, such as seasonal temperature change, daily traffic loads on bridge, etc.

The raw ground motion data is processed and stored in the COSMOS Strong Motion Data Format [4]. 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, and relative displacement). Also included is the Fourier amplitude spectrum.

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 [5]. 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 local/global 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 identified modal properties are also used in the model updating process.

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 displacement values are calculated by double integration of the narrow-band filtered acceleration data. The filter corner frequencies of each drift analysis depend on the first predominant frequency of the part of the structure for which the drift is calculated. The peak displacement values calculated during an event are stored in the database. Any drift value exceeding predefined threshold value will indicate a possible damage in the structure.

The BCSIMS system is set up to use various techniques of damage detection at different locations. 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. The first of the implemented algorithms is in the SIMS2 module. It is a statistical algorithm [6]. 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 [7]. These algorithms are:

i. Damage index method – [8]
ii. Mode shape curvature method – [9]
iii. Change in flexibility method – [10]
iv. Change in uniform load surface curvature – [11]
v. Change in stiffness method – [12]

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 [13] utilized two variations of stochastic flexibility methods. These methods are:

i. Stochastic Damage Locating Vector (SDLV) Technique – [14], based on the Damage Locating Vector (DLV) Technique – [15], [16].

ii. Proportional Flexibility Matrix Technique – [17]

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

Automated FEM updating is performed through the SIMS3 PC using the FEMTools 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 labeled 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 SUMMURY AND FUTURE WORK

The British Columbia Ministry of Transportation and the University of British Columbia have embarked on a program 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 100 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 www.BCSIMS.ca which allows for viewing of the strong motion network, structural stations, data, results and event reports. BCSIMS features some other capabilities that are discussed in more detail in [18].

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. Currently the system is being tested, and work with BC emergency management teams is underway to begin using the system.

ACKNOWLEDGEMENTS

The Authors would like to Acknowledge Dr. Palle Anderson and Andre Abreu of Structural Vibration Solutions, Aalborg Denmark. They have been the primary developers of much of the software components and have worked tirelessly to push the project forward. Also they would like to acknowledge Dr. Andreas Rosenberger from the Pacific Geosciences Centre for his considerable contributions to the project. The primary funding for this project has been provided by the British Columbia Ministry of Transportation and Infrastructure.

REFERENCES

[1] Wald, D.J., Quitoriano, V., Heaton, T.H., and Kanamori, H., (1999). Relationship between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California, *Earthquake Spectra*, **15:3**, 557-564.

[2] Katayama, T., Sato, N., and Saito, K., (1998). SI-Sensor for the Identification of Destuctive Ground Motion, Proc. Ninth World Conference of Earthquake Engineering, Tokyo-Kyoto, VII: 667-672

[3] Karim, K.R., and Yamazaki, F. (2002), Correlation of JMA instrumental seismic intensity with strong motion parameters, Earthquake Engng Struct. Dyn. 31:1191-1212

[4] COSMOS Strong Motion Programs Boards, (2001). Consortium of Organizations for Strong-Motion Observations Systems (COSMOS) Strong Motion Data Format, Ver 1.20 August 15, 2001

[5] Structural Vibration Solution A/S, (Copyright 1998-2012)., ARTeMIS Extractor Pro, Release 5.3

[6] Balmes, E., Basseville, M., Mevel, L., Nasser, H., Zhou, W., (2008) Statistical model-based damage localization: A combined subspace-based and substructuring approach, Structural Control and Health Monitoring, 15:857-875

[7] Farrar,. C., Jauregui, D., (1998). Comparitive study of damage identification algorithms applied to a bridge: 1. Experiment, Smart. Mater. Struct. 7: 704-719.

[8] Stubbs, N. and Kim, J.T., (1994). Field verification of a nondestructive damage localization and severity estimation algorithm, Texas A&M University Report prepared for New Mexico State University

[9] Pandey, A. K., Biswas, M. and Samman, M. M. (1991), Damage detection from changes in curvature mode shapes, J. Sound Vib. 145: 321–32

[10] Pandey, A. K. and Biswas, M. (1994). Damage detection in structures using changes in flexibility, J. Sound Vib., 169: 3–17

[11] Zhang, Z. and Aktan, A. E. (1995). The damage indices for the constructed facilities, Proc. 13th Int. Modal Analysis Conf., 2: 1520–9

[12] Zimmerman, D. C. and Kaouk, M. (1994), Structural damage detection using a minimum rank updates theory. J. Vib. Acoust., 116: 222–31

[13] Turek., M, Ventura, C.E., (2007), Calibrated Vibration Simulations for Design of SHM Systems, Proc. Of IMAC XXV, Orlando FL, Paper 249

[14] Bernal, D., (2006). Flexibility-Based Damage Localization from Stochastic Realization Results, ASCE Journal of Engineering Mechanics, 132:6 651-658

[15] Zonta, D., Bernal, D., (2006), Strain-Based Approaches to Damage Localization in Civil Structures, Proc. of IMAC XXIV, St. Louis, MO., Paper 197

[16] Bernal, D. (2002). Load vectors for damage localization, Journal of Engineering Mechanics, ASCE, 128:1 7-14.

[17] Duan, Z., Yan, G., Ou, J., Spencer, B.F., (2005). Damage localization in ambient vibration by constructing proportional flexibility matrix, Journal of Sound and Vibration, 284: 455-466 Dynamic Design Solutions N.V., (Copyright 1994-2012). FEMTools Version 3.5.3

[18] Ventura, C., Kaya, Y., (2012), Seismic Structural Health Monitoring of Bridges in British Columbia, CANADA, Proc. the15 World Confference of Erathquake Engineering, Lisbon, Portugal.