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AN INTEGRATED STRUCTURAL HEALTH MONITORING TOOL USING BUILDING INFORMATION MODELING

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Abstract: With increasing complexity of modern infrastructure, fast and accurate condition assessment of aging structures under extreme climatic events has shown significant attention to the infrastructure owners. Apart from preventing sudden catastrophic failures, vibration-based structural health monitoring (SHM) techniques ensure occupant safety and uninterrupted use of structures under normal operational conditions. Sensor-based high-quality data collection and subsequent data processing are central to the SHM strategies to undertake risk and hazard mitigation of structures in a timely manner. However, data-driven approaches are not enough to monitor a large amount of SHM data and undertake systematic decision making. Recently, Building Information Modeling (BIM) has become popular as a powerful modeling tool for design, construction, facility management, and life-cycle analysis of newer structures. In this paper, the BIM platform is utilized to develop an integrated visualization and monitoring tool to facilitate SHM of existing large-scale structures over their entire lifecycle. A large-span bridge in Thunder Bay, Ontario is used to demonstrate the proposed BIM-based SHM methodology.

1 INTRODUCTION

Large and complex structures, such as bridges, are exposed to a wide variety of environmental conditions and heavy traffic loads. In North America, repeated exposure to increasing traffic operations, extreme climatic conditions, and corrosive de-icing agents results in significant deterioration, including corrosion, fatigue, and other progressive damages in bridges. If these damages are not detected in a timely manner, they can result in catastrophic failure and major economic losses to the public. Structural Health Monitoring (SHM) is a systematic approach to monitor these structures under operational conditions to identify initial progression of damage and prevent any future failures (Lynch *et al.* 2016) based on the measured vibration data. Long-term SHM also enables infrastructure owners address issues associated with serviceability, including residual deformation or excessive vibration in bridges (Farrar and Worden 2013).

With the aid of advanced sensing technology, SHM provides continuous real-time monitoring of large-scale structures including large-span bridges. In general, a network of sensors is installed in key locations of the structures and the measurement data are collected under different traffic loads and environmental conditions. Once the data is collected, advanced signal processing techniques are employed to perform condition assessment of the structure (Sadhu *et al.* 2017; Barbosh *et al.* 2018). With increasing natural hazards and extreme climatic events, there is a real need for long-term monitoring of large-span bridges where the sensors are embedded, and the vibration measurements are collected from a large number of sensors in a continuous basis. Most of the current research efforts (Lynch *et al.* 2016) of SHM are focused on the development of sensing technologies to acquire rich vibration data and subsequently detect damages using system identification algorithms. However, in case of long-term monitoring, interpretation of such big data and visual representation of the evolution of damage are also critical for the bridge engineers to proactively undertake necessary maintenance operations. In the current work, BIM is utilized as an integrated tool for better visualization, condition assessment and decision-making tool to undertake SHM.

BIM is a hybrid modelling approach for conceptual design, construction, facility management and life-cycle analysis of new structures. Apart from serving a visualization software platform, it also offers an object-oriented modeling environment that enables a better understanding of a project and helping the design and construction team to share the information with the client and other stakeholders. With such capabilities, BIM can also be beneficial to monitor aging structures. Recently, Shirole and Chen (2006) highlighted the importance of electronic communication of life cycle information to improve real-time monitoring of bridges. An environmental life-cycle assessment was conducted where a building model developed in the BIM software was integrated with the structural analysis software (Bhusar and Akahre 2014). With such approach, all the vital information of design, analysis, and documentation were kept in one place that enabled a better communication among different parties. In another study, BIM was also used as an effective facility maintenance tool. A case study was conducted on a precast concrete bridge in UK where the modelling and visualization of the monitoring data was performed using Autodesk Revit® (Delgado *et al.* 2016).

Integrated health monitoring of structures becomes possible by developing sensor technology which helps in improving structural consistency, durability, system performance, and safety against natural disasters (Shakramanyan *et al.* 2012). Despite recent developments of intelligent SHM techniques, the developed systems still lack an efficient and integrated representation of sensor information over time. With the advent of BIM, the opportunities and challenges towards the digital representation of SHM information using the industry foundation classes (IFC) are gradually realized. Such conceptual approach was proposed for mapping monitored sensor information through IFC scheme that connected sensor modules with the BIM (Smarsly and Tauscher 2015). The different methodologies to perform the structural health monitoring for real-time responses was explained in (Maximilian and Kosmas 2016). The proposed framework integrated related information into BIM which helped in categorizing, documenting, and monitoring related information throughout the life-cycle of structures. However, the results obtained from the IFC did not provide sufficient entities to digitally represent the overall SHM system. Jeong *et al.* 2016 discussed the data management infrastructure for bridge monitoring purposes. In their investigation on NoSQL, a data management framework was developed for bridge monitoring while comparing the influence lines obtained from the sensor data and bridge information with the results from a numerical analysis.

2 INTEGRATED BIM-BASED SHM APPROACH

The proposed framework integrates the outcomes of SHM within a BIM platform. Long-term SHM of any structure urges the need of efficient visualization and faster interpretation of processed data. As shown in Fig. 1, the proposed approach includes four key steps: (a) approximate/preliminary engineering drawing of the structure, and (b) develop an accurate BIM model, (c) collection of sensor data, and (d) data processing and system identification. The first two steps are essential to BIM, whereas last two steps are part of the SHM.

With the aid of engineering drawings, the structural layout is built into a 3D model with the available generic parameters using Autodesk Revit®. This model gives a real time appearance of the structure with the structural properties and facilitates component identification during its service period. The BIM platform reduces the working space of structural analysis by linking the model to other structural analysis software, called Robot Structural Analysis (RSA®). The analysis results obtained from RSA® are saved as readable files for the parental platform. Apart from performing the static analysis, the results of dynamic analysis in RSA® help in monitoring the structure in a systematic manner during its service period.

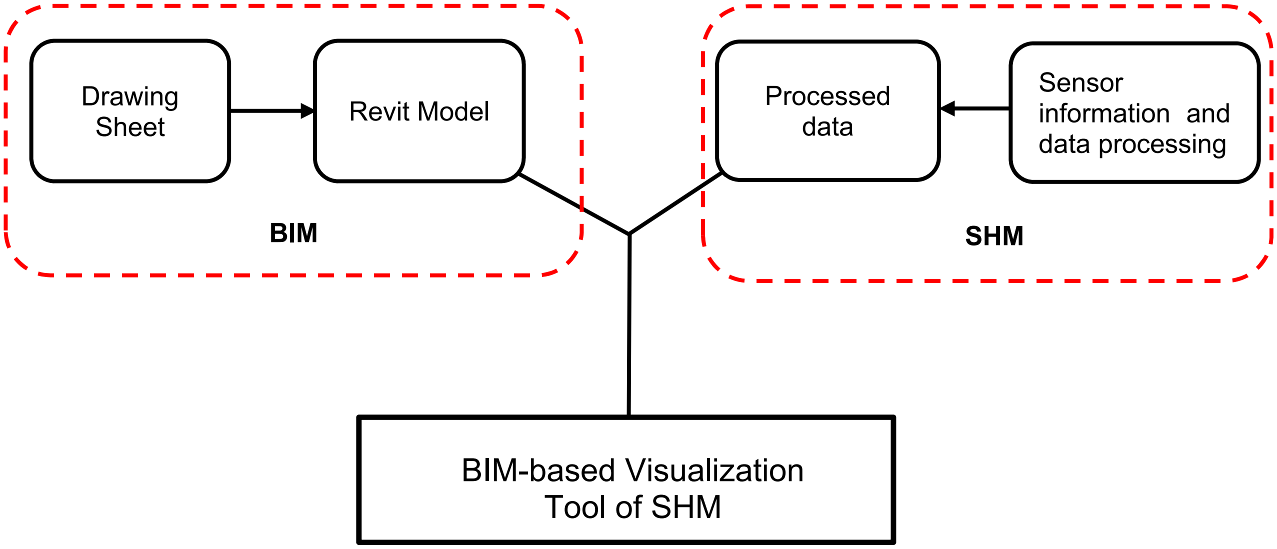


Figure 1. Flowchart of the proposed framework

To conduct SHM, sensors are installed in the structure and the collected data is processed using MATLAB® and the frequency domain information (i.e., Fast Fourier Transform (FFT)) are extracted for each sensor for every time period of data collection. These FFT plots are exported as JPEG files which can be visualized in Revit®. Using the FFTs, the natural frequencies of the bridge are identified which are linked with the BIM model using Revit®. All the results from static and dynamic analysis are projected in the BIM model. These results will facilitate monitoring the performance of the structure during each time period of data collection. The comparison between the identified natural frequencies based on SHM data and the finite element (FE) model gives better understanding towards the evolution of progressive changes and serviceability in the structure in a long-run.

3 CASE STUDY

3.1 SHM of the bridge

Figure 2. A long-span bridge in Thunder Bay, Ontario

A long-span bridge in Thunder Bay, Ontario was tested to demonstrate the proposed methodology. As shown in Fig. 2, the bridge is a reinforced-concrete bridge approximately 1000 ft long and 24 ft wide. The bridge was excited under a wide range of vehicles and the resulting vibrations were measured by six uni-axial sensors. As shown in Fig. 3(a) and Fig. 3(b), sensors were installed on the sidewalk of the bridge symmetrically with respect to the mid-span as shown in Fig. 4.

(a) (b)

Figure 3. (a) Vehicles running over the bridge during the test, (b) sensor placed on the side walk

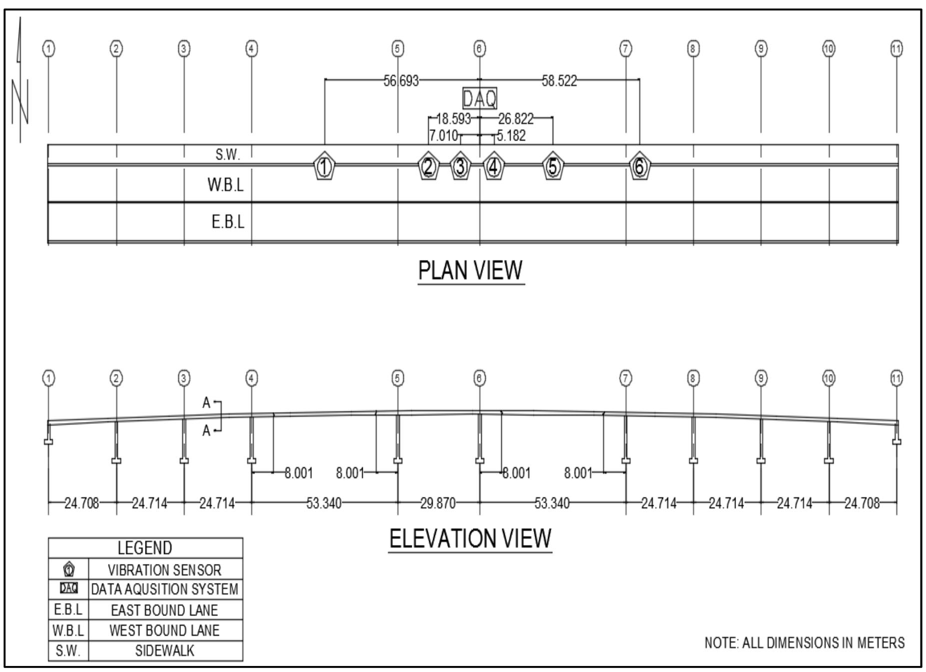
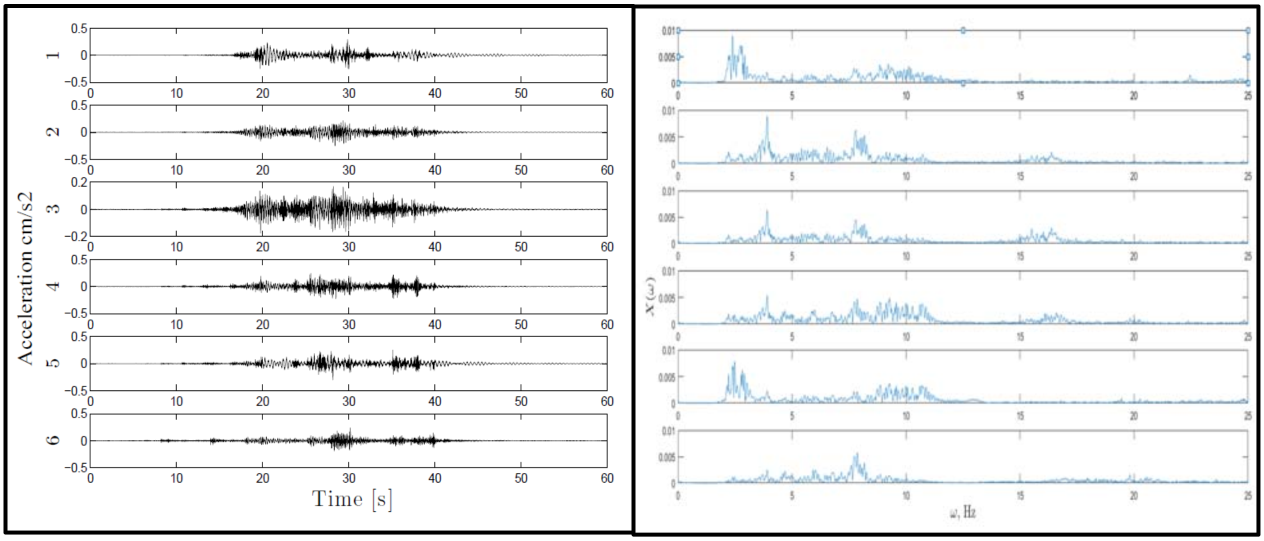


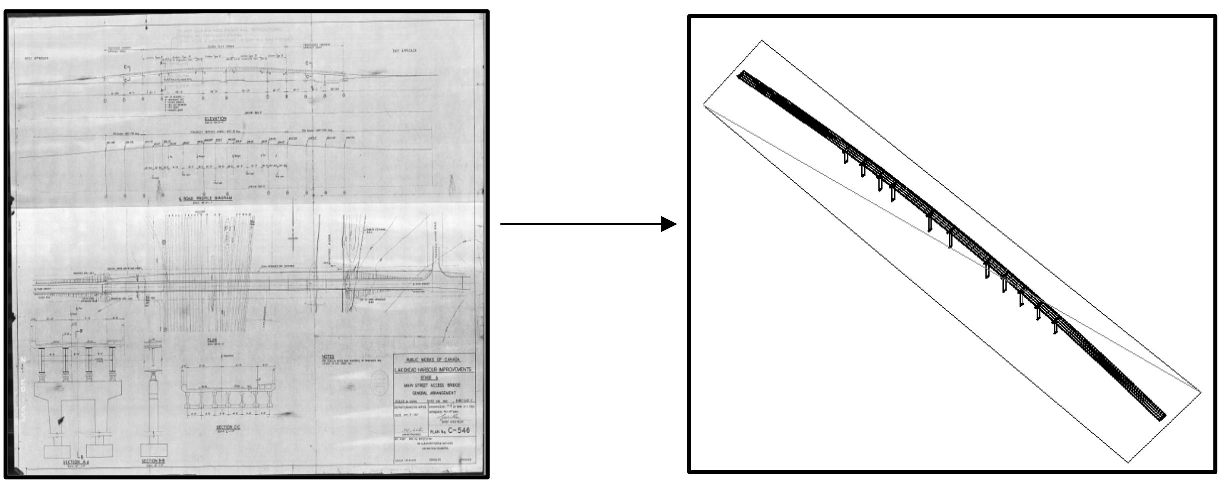
Figure 4. Location of sensors and layout of the bridge

All sensors were connected to the data acquisition (DAQ) that was placed at the middle of bridge as shown in Fig. 4 where the measured signals are transmitted to a laptop computer connected with the DAQ using a USB cable. Vertical acceleration was measured and fast Fourier transform (FFT) is used to represent the measured signal in frequency domain as shown in Fig. 5(a) and (b).



(a) (b)

Figure 5. (a) Measured vibration data, and (b) the Fourier spectra of the data



(a) (b)

Figure 6. (a) Available drawing sheets, (b) 3D Revit® model of the bridge

3.2 Implementation of BIM

As shown in Fig. 6, a computer model of the bridge is developed using Autodesk Revit® with the appropriate dimensions and material properties. The acquired sensor data as shown in Fig. 5(a) and 5(b) are included in the developed sensor entities and visualized directly onto the BIM model. The FFTs of each sensor obtained from MATLAB® are converted into JPEG files for better visualization of current modal parameters of the structures and included in Revit®. The FE results obtained from the RSA® are converted into PDF files. In order to foresee the sensor parameters and structural properties, their parameters as shown in Fig. 7 are assigned to the BIM model

Revit® can visualize the sensor schedule table including all the sensors as well as their entitled properties. For the current case study, different entities like reaction forces, moments and deflections, sampling frequency, MATLAB® figures, and sensor data are added to the sensor properties. One of the unique features of the sensor schedule table is that when a specific sensor is selected, the selected sensor will automatically highlight all the key important parameters assigned to that sensor. After defining the sensor schedule table, the results of sensor data and static analysis can be added to the model using "links" through different formats such as JPEG (images), PDF, XLSX, and EPS files.

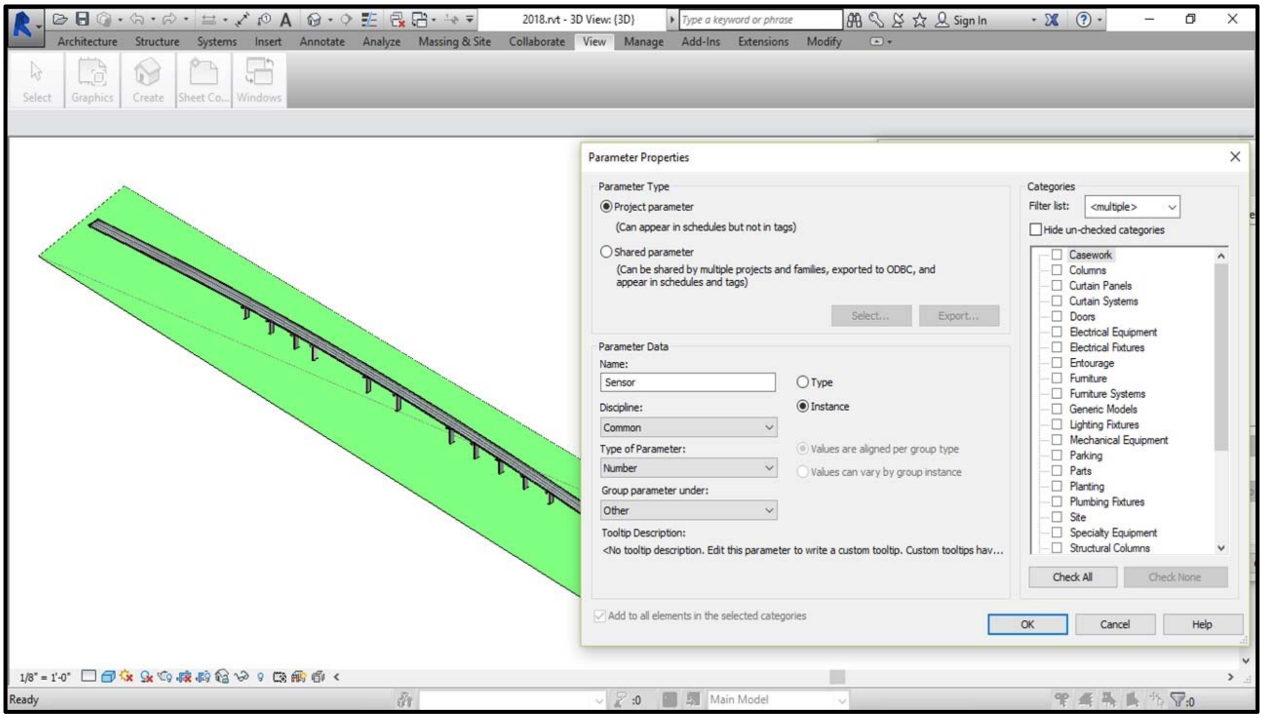
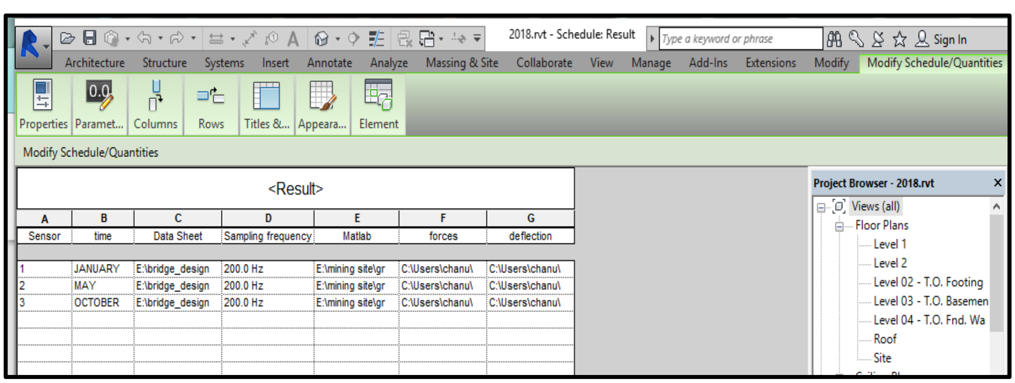
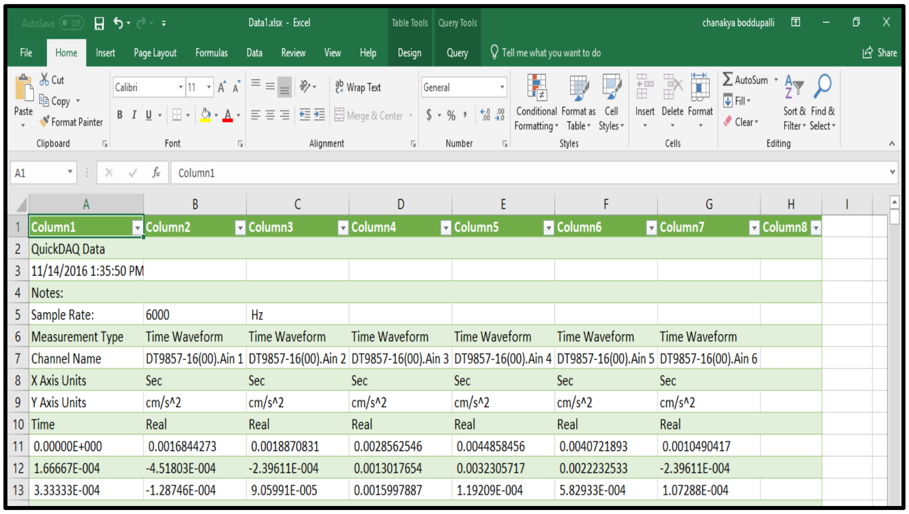


Figure 7. Revit® model with sensor parameter definition

As shown in Fig. 8(a), a dialog box is created in Revit® to list all the sequential data that are collected during the monitoring process. By selecting appropriate link, it is possible to see the details of the entire time-domain data or FFT plots at any given period of time as shown in Fig. 8(b-c). The time-domain data also enables in finding maximum acceleration of the structure that could be useful to check the overall serviceability of the bridge.

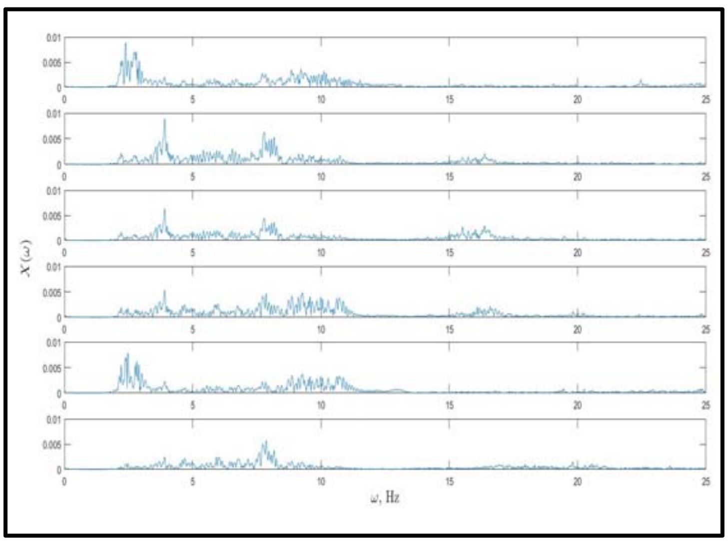


(a)



	A	B	C	D	E	F	G	H
1	Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8
2	QuickDAQ Data							
3	11/14/2016 1:35:50 PM							
4	Notes:							
5	Sample Rate:	6000	Hz					
6	Measurement Type	Time Waveform	Time Waveform	Time Waveform	Time Waveform	Time Waveform	Time Waveform	
7	Channel Name	DT9857-16(00).Ain 1	DT9857-16(00).Ain 2	DT9857-16(00).Ain 3	DT9857-16(00).Ain 4	DT9857-16(00).Ain 5	DT9857-16(00).Ain 6	
8	X Axis Units	Sec	Sec	Sec	Sec	Sec	Sec	
9	Y Axis Units	cm/s^2	cm/s^2	cm/s^2	cm/s^2	cm/s^2	cm/s^2	
10	Time	Real	Real	Real	Real	Real	Real	
11	0.00000E+000	0.0016844273	0.0018870831	0.0028562546	0.0044858456	0.0040721893	0.0010490417	
12	1.66667E-004	-4.51803E-004	-2.39611E-004	0.0013017654	0.0032305717	0.0022232533	-2.39611E-004	
13	3.33333E-004	-1.28746E-004	9.05991E-005	0.0015997887	1.19209E-004	5.82933E-004	1.07288E-004	

(b)



(c)

Figure 8. Automated data information

To improve the accuracy of the Revit® model, RSA® program is utilized to compare the SHM results with the FE model and update the model. Due to its compatibility with Revit®, RSA® is adopted to perform static analysis and conduct the stiffness calculation. First the bridge is designed based on the Canadian Highway Bridge Design Code (CHBDC) and then it is exported to RSA®. Once the model is set up, the loads were applied as per the CHBDC to analyze the static behaviour of the structure. Based on the typical seasons in a year, the loads are estimated accordingly. In January, a lot of snow is expected that are added as additional load along with the live loads and dead loads. Whereas, for the other seasons (i.e., May and October) the snow load is replaced with heavy traffic loads. Based on these assumptions, and load combinations from the CHBDC, structural analysis is performed in the RSA® and the results (i.e., reaction forces, moments, and deflections) are obtained as shown in Fig. 9. The converted PDF format of the RSA® file is linked to the sensor entity to characterize the performance of the structure. Based on the static analysis and SHM of the structure, stiffness of the bridge (RSA®) and natural frequencies (MATLAB®) are calculated. The obtained stiffness values from RSA® and natural frequencies from MATLAB® are compared to adhere the behavior of the structure under operation loads.

Autodesk Robot Structural Analysis Professional 2015
Author:
Address:
File: **1-25-2018.rtd**
Project: 1-25-2018

Node/Case	FX (kip)	FY (kip)	FZ (kip)
5/ 1	286.45	-2333.23	400.43
5/ 2	-291.39	959.35	0.87
6/ 1	258.62	2343.01	400.75
6/ 2	-281.34	-964.69	0.50
7/ 1	-59.09	-1623.83	396.02
7/ 2	-526.87	506.30	-0.41
8/ 1	-40.46	1614.05	396.24
8/ 2	-540.60	-499.61	-0.33
Case 1	LL1		
Sum of val.	0.00	0.00	3153.03
Sum of reac.	0.00	0.00	3153.03
Sum of forc.	0.0	0.0	-3153.03
Check val.	0.00	0.00	-0.00
Precision	2.60768e-003	2.01953e-017	
Case 2	thermal load		
Sum of val.	0.00	0.00	0.00
Sum of reac.	0.00	0.00	0.00
Sum of forc.	-0.00	-0.00	0.0
Check val.	0.00	0.00	0.00
Precision	1.63861e-006	1.00000e+000	

Figure 9. Reaction forces obtained from the RSA®

4 CONCLUSIONS

In this paper, a BIM based SHM tool is proposed that serves as a primary basis of collected information of long-term monitoring in a systematic manner. The proposed tool serves as an excellent visualization tool to evaluate the evolution of progressive damage as well as serviceability status in a user-friendly manner. Such an integrated tool allows the practising engineers in organizing, processing, and visualizing the sensor data from the monitoring system, updating relevant finite element models, and providing valuable feedback for structural retrofitting in a unified platform. The proposed bridge information modeling method can be considered as a user friendly and economical framework for condition assessment of large-scale structures.

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