Sensing-based Structural Health Monitoring and Novel Data-driven Approach for Bridges Using Ambient Vibration Testing

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Abstract

Existing integrity evaluation approaches for bridges mostly depend on visual inspections and assumption-based theoretical models. In more recent years, structural health monitoring systems (SHM) have been permanently installed on a few landmark bridges in North America. Due to several shortcomings including frequent maintenance, wired systems, difficulties in installation, and low levels or non-existent data analysis, these systems have been unsuccessful in providing a practical insight into a structure's integrity. As a result, they have not been adopted on a large scale. Therefore, there is a need to develop a novel SHM system that is easy to install, wireless, and based on in-depth data analysis to provide actionable insights about bridge integrity to asset owners.

This paper presents a state-of-the-art approach developed to provide an advanced structural health monitoring solution using ambient vibration testing to evaluate the integrity of bridges. This novel method is data-driven and evaluates the condition of all major bridge components including foundations, piers, abutments, bearings, deck, and potential scour from sensors deployed only at the deck. In this paper, the performance of this method is shown on three continuous three-span bridges in Northwestern Ontario including the Mackenzie River Twin Bridges and the Pic River Bridge owned and operated by the MTO. The ambient vibration data is collected for only a few hours using highly sensitive and synchronized sensors across six channels thanks to a combination of triaxial velocimeters and triaxial accelerometers. Through in-depth processing of the measured data, multiple dynamic properties (natural frequencies, high-quality animated 3D mode shapes, and damping ratios) including higher modes are precisely identified, serving as the stiffness baseline of a bridge.

The damage detection approach is based on comparing a bridge's stiffness baselines (dynamic properties) with similar bridges within a database of healthy and unhealthy bridges and by periodically comparing them with the bridge itself over the bridge's lifetime. This unique approach precisely examines any change in the mode shapes and resonance frequencies to detect, locate, and quantify structural damage that may compromise a bridge's integrity. By comparing the extracted dynamic properties with the expected ones from a healthy bridge, the observed anomalies in the mode shapes can be correlated to physical damage and identifying the damaged structural component. State-of-the-art technology is capable of significantly enhancing the performance of structural health monitoring systems and contributing to a rapid and more reliable assessment of bridges.

Keywords: Ambient Vibration Test (AVT), Structural Health Monitoring (SHM), Vibration Sensors, Natural Resonance Frequencies, 3D Mode Shapes, Damage Detection

1) Introduction

Current structural assessment approaches mostly rely on visual inspections and assumption-based theoretical models to evaluate an existing structure, both of which are burdensome and provide results that may differ from reality. Furthermore, existing condition assessment tests may be destructive and evaluate only a localized portion of a bridge. By considering only a localized portion of a bridge, the detected cracks and anomalies may have not had any effect on the overall integrity of the bridge.

In addition to visual inspections and destructive tests, vibration sensors have been traditionally installed permanently on bridges only to send alarms when vibration levels exceed certain thresholds. Some issues associated with these sensors include enormous amounts of data over the years not yielding any practical insight about the overall integrity of the bridge, installation difficulties such as lengthy cabling, and maintenance. As a result, traditional structural health monitoring (SHM) systems have been unviable to be installed on a large scale.

Since existing SHM systems have the aforementioned issues, unique wireless vibration sensors, data analysis algorithms, and software have been developed to extract dynamic properties (stiffness baselines) from the gathered vibration data to provide practical insights about the global integrity of bridges and detect, locate, and quantify damage. Sensing-based structural health monitoring increases a bridge's reliability and the length of its service life by providing results based on the actual performance of the bridge. Several research studies have proven the reliability of ambient vibration testing to extract dynamic properties [1-13].

Sensing-based structural health monitoring is briefly demonstrated in Figure 1 [14-16]. This approach directly utilizes the in-situ derived modal properties and therefore bypasses the need for detailed structural drawings and finite element (F.E.) analysis models. Sensequake patented technology, 3D-SAM™ [17], can perform both structural health monitoring and seismic assessment on existing structures solely based on ambient vibration sensing data.

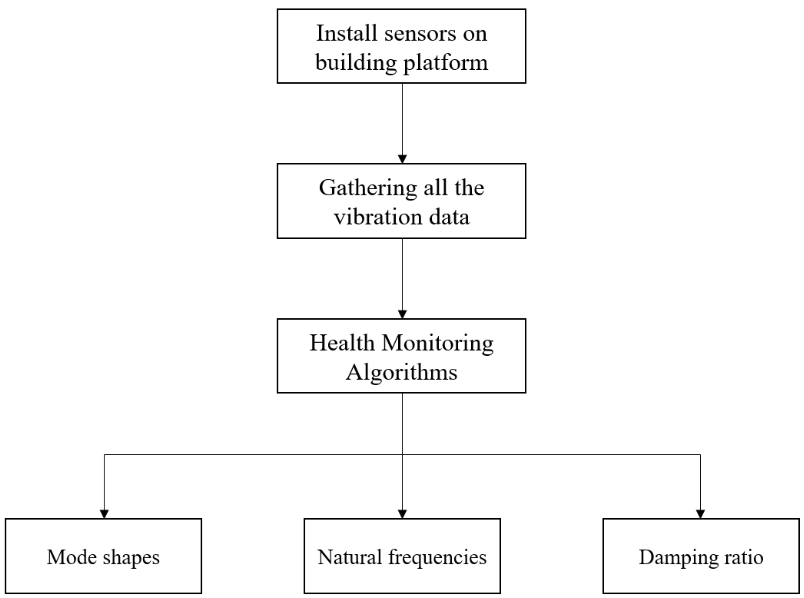


Figure 1: Methodology for sensing-based structural health monitoring

This study is focused on the ambient vibration data gathered from three continuous bridges in Ontario including the Mackenzie River Twin Bridges and Pic River Bridge. The Mackenzie River Twin Bridges were built in 2011 outside of Thunder Bay, Ontario (Figure 2). The Twin Bridges are continuous three-span and, at the time of construction, were North America's largest field-cast ultra-high-performance concrete-connection bridges. The Pic River Bridge is located along the Trans-Canada Highway 17, approximately 7 kilometres East of the town of Marathon in Ontario (Figure 3). The bridge was originally constructed in the early 1960s as a 3-span overhead truss bridge. In 2016, the bridge was reconstructed, utilizing the existing 1960s pier foundations, as a 3-span, steel girder, concrete deck bridge. State-of-the-art technologies are capable of significantly enhancing the performance of structural health monitoring systems and contributing to a rapid and more reliable assessment of bridges.

Figure 2: Mackenzie River Twin Bridges, Ontario

Figure 3: Pic River Bridge, Ontario

2) Objective and Methodology

The purpose of this paper is to perform an advanced ambient vibration-based integrity evaluation of three continuous bridges in Ontario including the Mackenzie River Twin Bridges and Pic River Bridge. The first step to achieve this goal is to perform a rapid non-destructive ambient vibration test on a bridge using highly sensitive and synchronized sensors [18] with six channels of data (acceleration and velocity in XYZ). Afterward, a few weeks of in-depth post-processing in both frequency and time domains is performed on the gathered vibration data to extract dynamic properties (natural frequencies, high-quality animated 3D mode shapes, and damping ratios) which correspond to the as-is condition of a bridge. Using the results generated through the analysis, the condition of all major bridge components including foundations, piers, abutments, bearings, deck, and scouring potential can be evaluated from sensors that were deployed only at the deck. Finally, the last step is to assess the overall structural integrity of the bridge. The steps to extract dynamic properties for Mackenzie River Twin Bridges are briefly depicted in Figure 4.

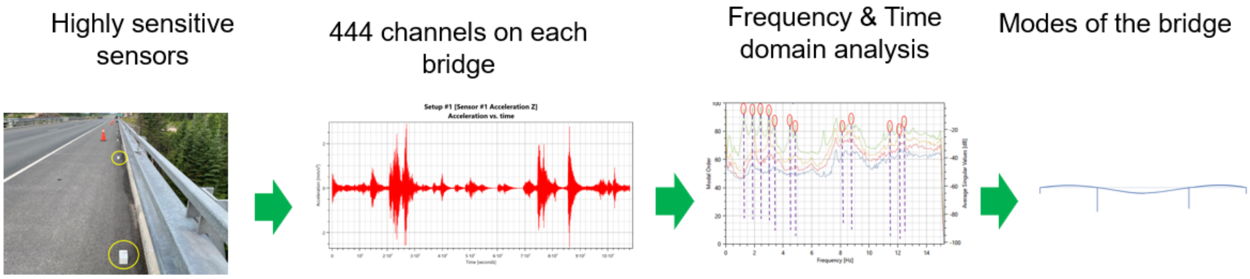


Figure 4: Steps used for the structural health monitoring of Mackenzie River Twin Bridges

3) Sensing Test

Comprehensive ambient vibration sensing tests are designed and performed on a structure to derive its dynamic properties (natural frequencies, mode shapes, and damping ratios). These tests provide important information about the current condition of the structure. Sensequake Larzé wireless sensors [18] are utilized to perform sensing tests and gather ambient vibration data. These sensors are capable of measuring the horizontal and vertical vibrations in structures as presented in Figure 5 (a). A smartphone application is used to configure the sensor network as presented in Figure 5 (b).

Figure 5: (a) Sensequake Larzé sensors [18]; (b) Larzé control application

The following are the main characteristics of the sensors:

- Six channels of velocity and acceleration data (covering a wide range from very small to large vibrations);
- Very low-noise sensor;
- Microsecond precision synchronization;

- Accurate synchronization without sensor communication for several hours - ideal for large civil engineering structures;
- Easy configuration through a phone application;
- Compact size;
- Wireless data transfer through Wi-Fi;
- Battery-powered and rechargeable.

The sampling frequency for a sensing test can be selected based on the type of structure. The sensor's analog-to-digital converters operate at much higher sampling rates and further decimate the data to achieve higher signal-to-noise ratios.

The Mackenzie River Twin Bridges were tested in July 2023 as presented in Figure 6 with a sampling frequency of 122 Hz. The average temperature on the day of testing was around 18 ℃. To extract the dynamic properties of the Mackenzie River Twin Bridges, 74 locations on each bridge were selected to deploy wireless sensors and collect ambient vibration data across six channels resulting in 444 channels per bridge.

Figure 6: Testing of the Mackenzie River Twin Bridges

The sensor layout for a sensing test is designed considering the geometry, structural configuration, and current condition of a bridge. The detailed sensor layout to gather ambient vibration data from the Mackenzie River Twin Bridges is presented in Figure 7. After the test, the gathered ambient data is transferred to a PC via a USB connection or through Wi-Fi.

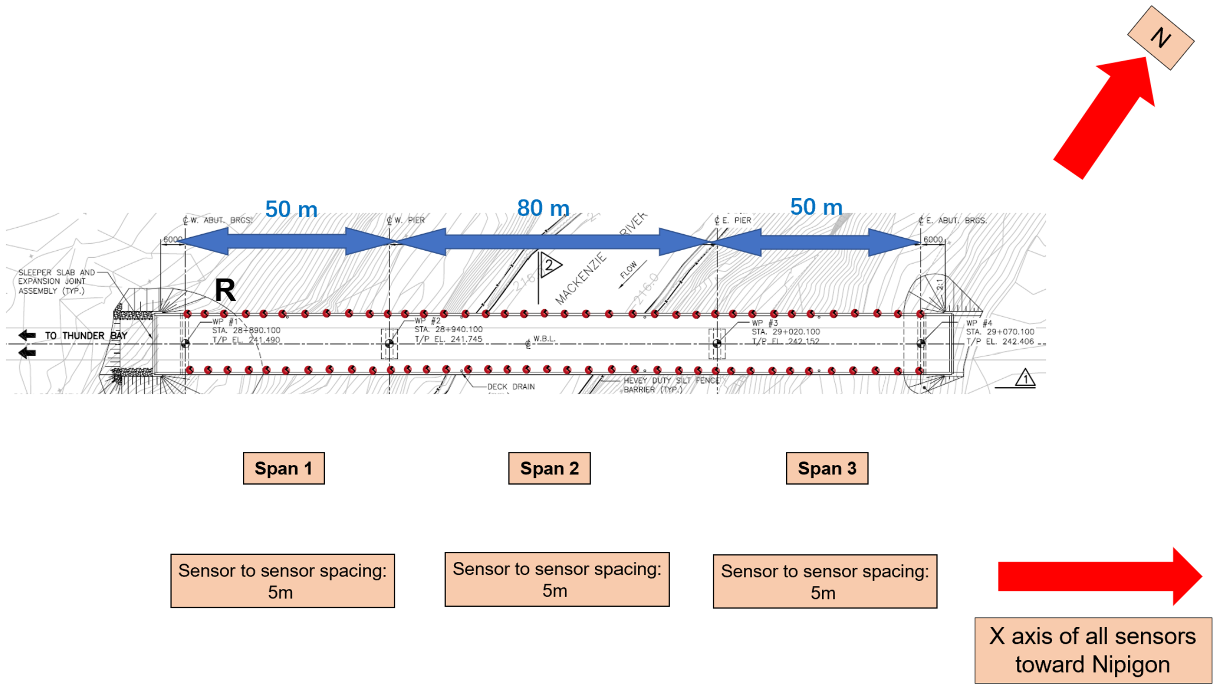


Figure 7: Sensor layout of the Mackenzie River Twin Bridges (Westbound)

4) Stiffness Baseline

Through in-depth post-processing of the vibration data gathered during a sensing test, stiffness baselines (dynamic properties) including natural frequencies, 3D mode shapes, and damping ratios are identified. One of the most robust and reliable techniques is used to extract stiffness baselines (dynamic properties) of structures called the Subspace Stochastic Identification (SSI) method [6]. Rigorous criteria are used to identify structural modes and distinguish them from noises. All structural modes are confirmed through precise processes and criteria such as Modal Assurance Criteria (MAC), acceptable range of damping ratio, real-portion of mode shapes, and confirmation from both time and frequency domain techniques. More details about these techniques can be found in [19].

Identifying the stiffness baselines (dynamic properties) of a structure is principal for comprehending its current condition. The baseline of a structure is unique to its current structural geometry, integrity, and stiffness. Generally, for a bridge, the existence of well-formed symmetrical continuous mode shapes is linked to overall stability, free of any local or global anomaly. Interpreting the stiffness baseline of a bridge through comparison with a unique database of healthy and unhealthy bridges helps in understanding the condition of the bridge. Sensequake's database of stiffness baseline properties of healthy and unhealthy bridges includes a wide range of different bridge types, including girder (beam), truss, arch, cantilever, suspension, and cable-stayed bridges that have been tested multiple times over the years. The database contains records of unhealthy and asymmetric behaviours observed in structural modes, such as excessive movement at the pier locations, distorted mode shapes, and changes in natural frequencies due to progressive symmetric degradation, which have been correlated with the as-is condition of the bridge.

This study is focused on the ambient vibration data gathered from three continuous bridges in Ontario including the two Mackenzie River Twin Bridges and Pic River Bridge. Four sensing tests were performed on the Pic River Bridge using the wireless sensors. After in-depth post-processing of the gathered ambient vibration data, seven sets of dynamic properties (natural frequencies and 3D mode shapes) were identified for the bridge. The natural frequencies extracted for the Pic River Bridge from the first sensing test performed in October 2021 are as follows 1.11 Hz, 1.60 Hz, 2.12 Hz, 2.63 Hz, 3.58 Hz, 4.15 Hz, 6.03 Hz. An average damping ratio of 1.7% was detected for the Pic River Bridge. The variations of the first natural frequency within a 2-year period are presented in Figure 8. Natural frequencies must be compared in summer and winter separately since they are sensitive to temperature. As presented in Figure 8, both summer and winter frequencies are stable. A reduction in frequency could indicate a symmetrical deterioration in the bridge which will not be visible with mode shape comparison. Symmetrical degradation is a consistent weakening of the structural components, causing a drop in natural frequency. Despite this reduction, the symmetry of the mode shape may still be retained.

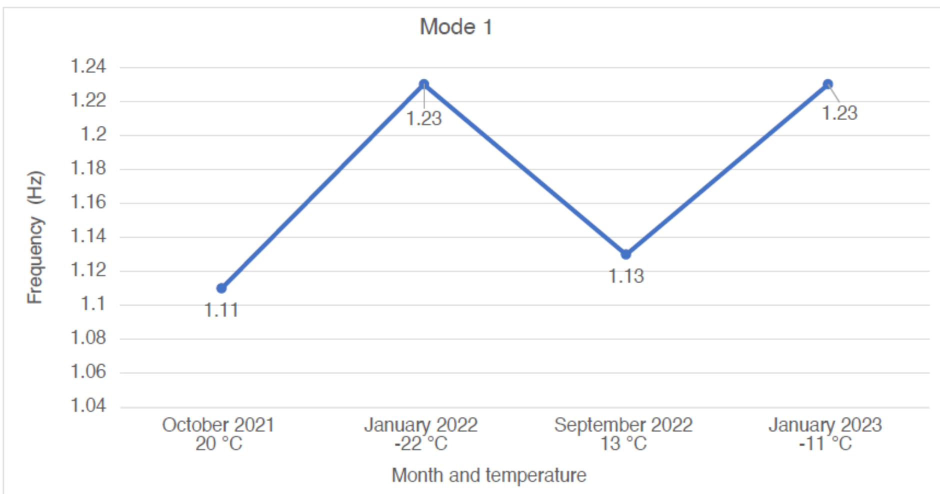


Figure 8- Variations of the first natural frequency within a 2-year period

In addition to symmetrical deterioration, bridges could undergo asymmetrical degradation. Asymmetrical degradation affects the uniformity, continuity, and symmetry of the mode shape. This asymmetry originates from an uneven distribution of stiffness between two edges of bridges. The mode shapes extracted for the Pic River Bridge from the first sensing test are presented in Figure 9.

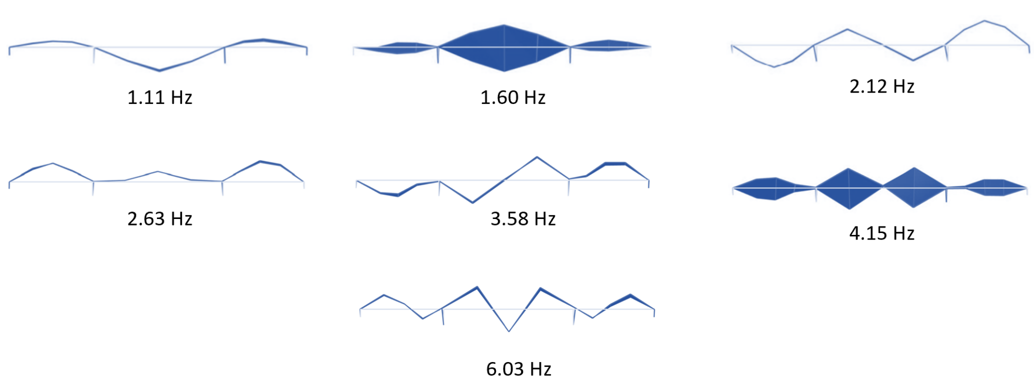


Figure 9: Mode shapes of the Pic River Bridge extracted from the first sensing test

Comparisons of the first vertical and torsional mode shapes extracted from the four sensing tests on the Pic River Bridge are presented in Tables 1 and 2 respectively. By comparing the dynamic properties of the Pic River Bridge to similar bridges within the unique database, no major anomaly or damage is observed and the bridge exhibits healthy structural behaviour. After completing the four sensing tests, the “range of stable baselines” was mathematically established for the Pic River Bridge using mode shape distortion area criteria and frequency thresholds. Comprehensive information about these thresholds will be provided by the authors in an upcoming journal paper.

Table 1- Comparison of the 1st vertical mode shape of Pic River Bridge

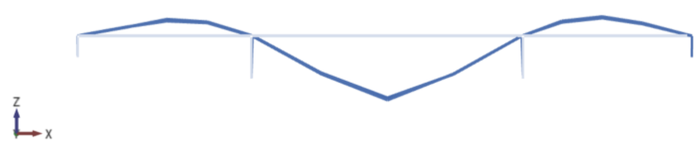
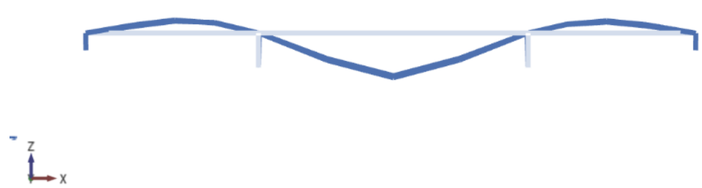
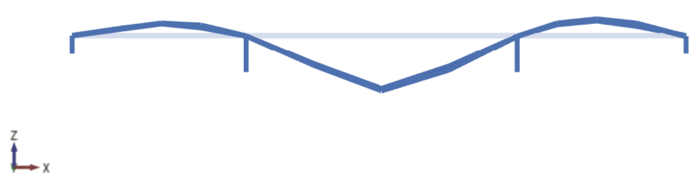
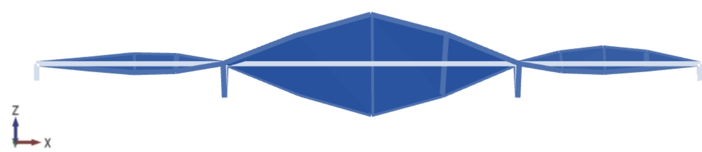
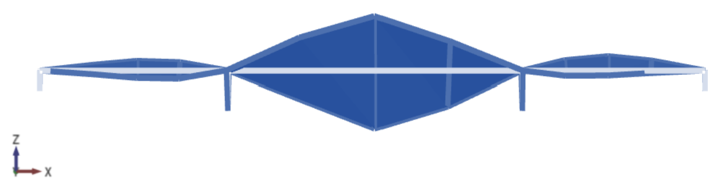
Test	Temperature	Frequency (Hz)	Mode Shape
1	20 °C	1.11	
2	-22 °C	1.23	
3	13 °C	1.13	
4	-11 °C	1.23	

Table 2- Comparison of the 1st torsional mode shape of Pic River Bridge

Test	**Temperature**	**Frequency (Hz)**	**Mode Shape**
1	20 °C	1.60	
2	-22 °C	1.74	
3	13 °C	1.64	
4	-11 °C	1.77	

After in-depth post-processing of the ambient vibration data gathered from Mackenzie River Twin Bridges in July 2023, several sets of dynamic properties (natural frequencies and 3D mode shapes) were identified for the bridges. The first vertical mode shape extracted for Mackenzie River Bridges (Eastbound and Westbound) is presented in Figure 10.

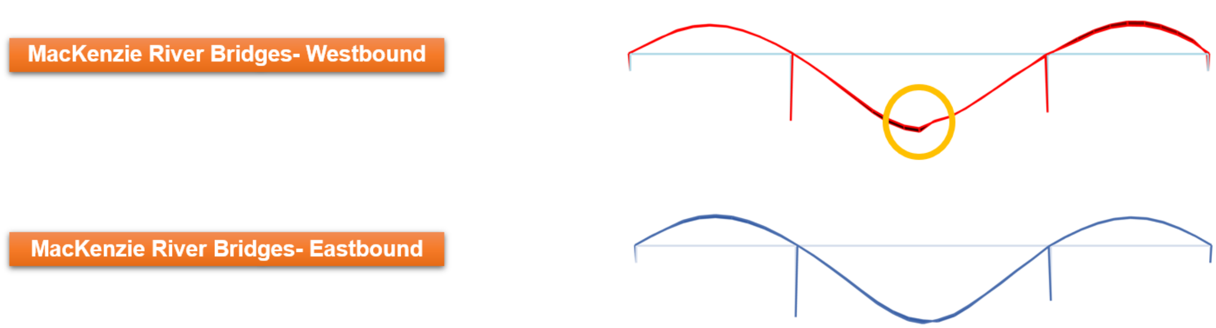


Figure 10: 1st vertical mode shape of the Mackenzie River Bridges (Eastbound and Westbound)

By comparing the dynamic properties of Mackenzie River Twin Bridges to similar bridges within the database, no major damage is observed. However, an anomaly corresponding to an asymmetrical distribution of stiffness between two edges of the bridge is observed in the middle span of one of the Twin Bridges as presented in Figure 10. Detailed inspection at that location and future monitoring of the bridge were recommended as the next steps. Comprehensive information about this study will be provided by the authors in an upcoming journal paper.

5) Conclusion

This paper presented a state-of-the-art approach developed to provide an advanced structural health monitoring solution using ambient vibration testing to evaluate the integrity of bridges. In this study, the performance of this method on three continuous three-span bridges in Northwest Ontario including the Mackenzie River Twin Bridges and Pic River Bridge was presented. The novel damage detection approach is able to detect, locate, and quantify structural damage that may compromise a bridge's integrity by comparing its stiffness baselines (dynamic properties) with similar bridges within the database of healthy and unhealthy bridges and by periodically comparing them over the bridge's lifetime.

As was presented, through in-depth processing of the measured data, multiple dynamic properties (natural frequencies, high-quality animated 3D mode shapes, and damping ratios) were precisely identified for the Mackenzie River Twin Bridges and Pic River Bridge. The variations of the first natural frequency within a 2-year period were identified for the Pic River Bridge. By comparing the mode shapes of the Pic River Bridge to similar bridges within the unique database, no major anomaly or damage was observed and the bridge exhibited healthy structural behaviour. After completing the four sensing tests, the "range of stable baselines" was mathematically established for the Pic River Bridge using mode shape distortion area criteria and frequency thresholds. By comparing the dynamic properties of Mackenzie River Twin Bridges to similar bridges within the database, no major damage was observed. However, an anomaly corresponding to an asymmetrical distribution of stiffness between two edges of the bridge was observed in the middle span of one of the Twin Bridges. Comprehensive information about the studies on the three bridges will be provided by the authors in an upcoming journal paper.

6) Acknowledgements

The three bridges (Mackenzie River Twin Bridges and Pic River Bridge) mentioned in this study are owned and operated by the Ministry of Transportation of Ontario- Northwestern Regional Office.

7) References

[1] Trifunac, M. D. (1972). Comparisons between ambient and forced vibration experiments. Earthquake Engineering & Structural Dynamics, 1(2), 133–150. https://doi.org/10.1002/eqe.4290010203

[2] Lamarche, C., Paultre, P., Proulx, J., & Mousseau, S. (2008). Assessment of the frequency domain decomposition technique by forced-vibration tests of a full-scale structure. Earthquake Engineering & Structural Dynamics, 37(3), 487–494. https://doi.org/10.1002/eqe.766

[3] Idris, Nurul Shazwin & Boon, Koh & Kamarudin, Ahmad Fahmy & Zaini Sooria, Sherliza. (2016). Ambient Vibration Test on Reinforced Concrete Bridges. MATEC Web of Conferences. 47. 02012. 10.1051/matecconf/20164702012.

[4] Omenzetter, Piotr & Beskhyroun, Sherif & Shabbir, Faisal & Chen, Ge-Wei & Chen, Xinghua & Wang, Shengzhe & Zha, Alex. (2013). Forced and ambient vibration testing of full-scale bridges. 10.13140/2.1.1168.5448.

[5] Bayraktar, Alemdar & Altunişik, Ahmet & Sevim, Barış & Türker, Temel. (2010). Ambient Vibration Tests of a Steel Footbridge. Journal of Nondestructive Evaluation. 29. 14-24. 10.1007/s10921-009-0061-9.

[6] Ventura, Carlos & Carvajal, Juan-Carlos & Proulx, Tom. (1970). Structural Assessment of Damaged Bridges Using Ambient Vibration Testing. 10.1007/978-1-4419-9825-5_5.

[7] Kudu, Fatma & Bayraktar, Alemdar & Bakir, Pelin & Türker, Temel & Altunişik, Ahmet. (2014). Ambient vibration testing of Berta Highway Bridge with post-tension tendons. Steel and Composite Structures. 16. 10.12989/scs.2014.16.1.021.

[8] Chen, Xinghua & Omenzetter, Piotr & Beskhyroun, Sherif. (2012). Ambient vibration tests and analysis of a multiple-span elevated bridge. 10.13140/2.1.3151.5200.

[9] Toydemir, Burak & Kocak, Ali & Sevim, Barış & Zengin, Basak. (2017). Ambient vibration testing and seismic performance of precast I beam bridges on a high-speed railway line. Steel and Composite Structures. 23. 557-570. 10.12989/scs.2017.23.5.557.

[10] Cunha, Alvaro & Calçada, Rui. (2000). Ambient Vibration Test of a Steel Trussed Arch Bridge, #374. 1.

[11] Abdel Zaher, Ahmed & Rabei, Mohammed & El-Attar, Adel & Kunieda, Minoru & Nakamura, Hikaru. (2006). Ambient Vibration Test of Aswan Cable Stayed Bridge. Journal of Applied Mechanics. 9. 85-93.. 10.2208/journalam.9.85.

[12] Chen, Xinghua & Omenzetter, Piotr & Beskhyroun, Sherif. (2014). Ambient vibration testing, system identification and model updating of a multiple-span elevated bridge. 10.13140/2.1.3594.9124.

[13] Valle, Siddartha & Cristobal, KC & Catapang, RM & Latoza, JD & Marocom, DA & Ramos, RM & Reyna, KM & Luna, LL. (2019). Modal Analysis of the Bridge of Promise via Ambient Vibration Test (AVT). 27.

[14] Mirshafiei, F. (2015). A novel three-dimensional seismic assessment method (3D-SAM) for buildings based on ambient vibration testing. McGill University, Canada.

[15] Mirshafiei, F., & McClure, G. (2016b). Modified three-dimensional seismic assessment method for buildings based on ambient vibration tests: extrapolation to higher shaking levels and measuring the dynamic amplification portion of natural torsion. Earthquake Engineering & Structural Dynamics, 45(12), 2011–2026. https://doi.org/10.1002/eqe.2746

[16] Mirshafiei, F., Mirshafiei, M., & McClure, G. (2017b). A new three-dimensional seismic assessment method (3D-SAM) for buildings based on experimental modal analysis. Computers & Structures, 180, 125–137. https://doi.org/10.1016/j.compstruc.2016.11.014

[17] Sensequake. (2024), 3D-SAM^{TM}, Software for Operational Modal Analysis and Sensing-based Seismic Analysis, https://www.sensequake.com/larze

[18] Larzé. Sensequake. (2024), Larzé^{TM}, Wireless highly sensitive vibration sensors, https://www.sensequake.com/larze

[19] Brincker, R., & Ventura, C. E. (2015b). Introduction to Operational modal analysis. https://doi.org/10.1002/9781118535141