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SEISMIC STRENGTHENING AND STRUCTURAL HEALTH MONITORING OF PORTAGE CREEK BRIDGE

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ABSTRACT

Located in Victoria, British Columbia (BC), Canada, the Portage Creek Bridge is a 124 m long, three-span structure with a reinforced concrete deck supported on two reinforced concrete piers, and abutments on H piles. The bridge is part of a disaster route, and it was designed prior to the introduction of current bridge seismic design codes and construction practices. Seismic evaluation of the bridge using the current codes indicated that the two tall columns of Pier No. 1 will form plastic hinges under an earthquake resulting in additional shear force to the short columns of Pier No. 2. The two columns of the bridge pier were strengthened with GFRP (Glass Fibre Reinforced Polymer) wraps, and instrumented with eight bi-directional rosette type strain gauges and four long gauge fibre optic sensors attached to the outer layer of the wraps. In addition, two 3-D Crossbow accelerometers are installed on the pier cap above the columns and a traffic web-cam mounted above the deck at the pier location. The main intention behind the instrumentation and the field tests was to confirm that the strains in the FRP wraps remain below the serviceability limits during normal operation of the bridge. The instrumentation is also intended to be used for capturing the bridge behaviour under major earthquakes. The paper discusses the strengthening and monitoring schemes briefly and presents the analysis of the monitoring data collected over a period of time. Static and dynamic tests were also conducted on the structure periodically. The data collected so far have proved the reliability of the instrumentation system and confirms that the levels of strains in the FRP wraps are acceptable. Only minor earthquakes have been registered in the area so far. Perturbation in strain readings has been very small due to those events

Introduction

This paper describes the seismic strengthening and remote structural health monitoring for a Disaster-Route bridge in British Columbia (BC), Canada. In 1982, the BC Ministry of Transportation designed the Portage Creek Bridge, as shown in Fig. 1, in-house. Located in the City of Victoria, British Columbia, the bridge crosses Interurban Road and Colquitz River at McKenzie Avenue. The bridge is described as a 124 m (407 ft) long, three-span structure with a reinforced concrete deck supported on two reinforced concrete piers, and abutments on H piles (Fig. 2). The deck has a roadway width of 16.2 m (53 ft) with two 1.98 m (6’6”) sidewalks and aluminium railings. The bridge was designed prior to the introduction of current bridge seismic design codes and construction practices. Therefore, it was not designed to resist

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the earthquake forces that are required by today's standards (FHWA, 1995; CAN/CSA-S6-88, 1988; CAN/CSA-S6-00, 2005). It does appear, however, that consideration was given to some seismic aspects, as evidenced by a review of the drawing details. As the bridge is classified as a Disaster Route bridge, it was to be retrofitted to prevent collapse during a design seismic event, with a return period of 475 years (i.e., events having 10% probability of occurrence in 50 years).

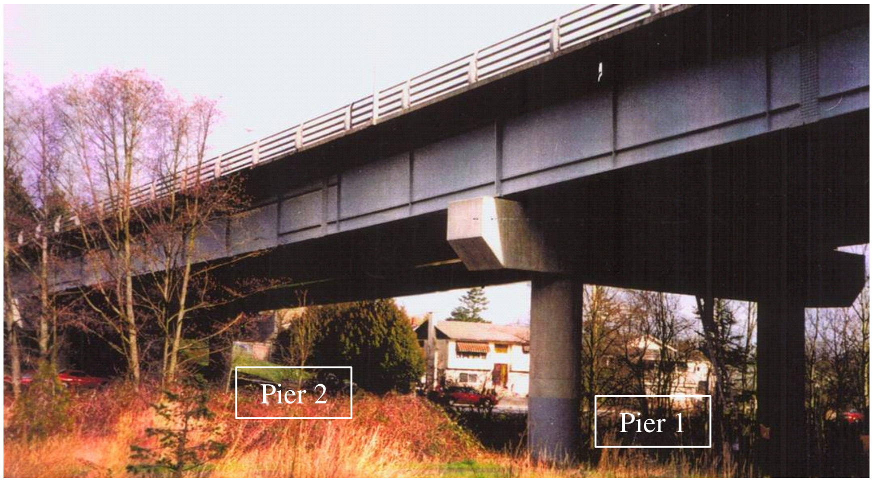


Figure 1. Portage Creek Bridge in Victoria, British Columbia.

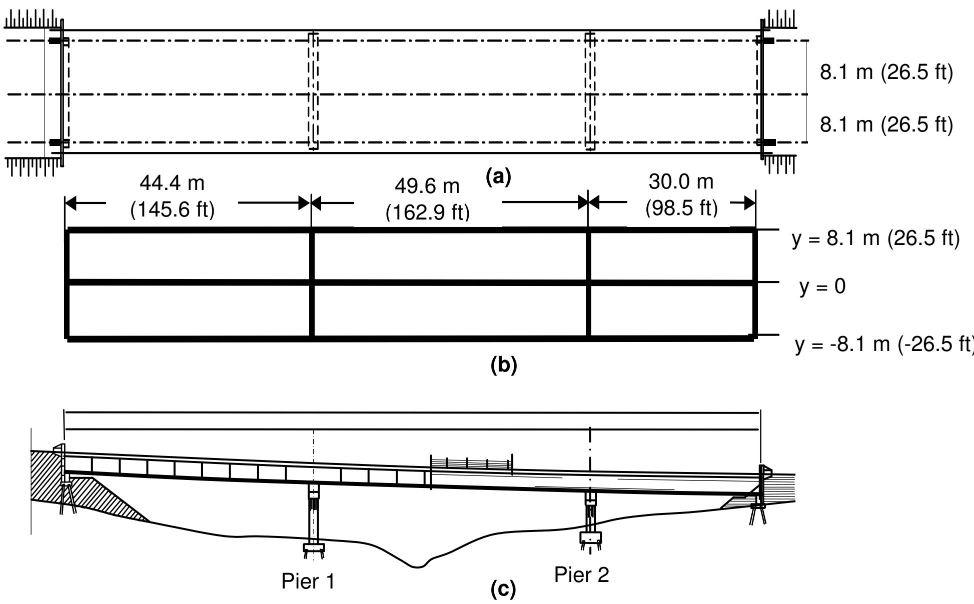


Figure 2. (a) Plan of Portage Creek Bridge, (b) Simplified Bridge Geometry, and (c) Elevation.

The paper presents the seismic evaluation of the as-built structure of Portage Bridge, design of the GFRP wrap system for strengthening the deficient columns, and development of an integrated structural health monitoring system for the bridge. Conventional materials and methods were used to retrofit the other parts of the bridge. Based on the dynamic analysis of the bridge, it was determined that the two tall columns of Pier No. 1 as shown in Figs. 2 and 3 would form plastic hinges under an earthquake. As a result of these hinges, the short columns of Pier No. 2 would attract additional shear due to redistribution of internal forces. A non-linear static pushover analysis indicates that the short columns would not be able to form plastic hinges prior to failure in shear. Therefore, it was decided that Fibre Reinforced Polymer Wraps (FRPs) should be used to strengthen the short columns for shear without increasing the moment capacity.

The FRP Wraps and the monitoring system was designed and implemented under the technical leadership of ISIS (Intelligent Sensing for Innovative Structures) Canada. ISIS Canada is a publicly funded Network of Centres of Excellence (NCE) that involves major universities, industry, government agencies, and infrastructure owners in Canada to conduct research in structural rehabilitation and monitoring using innovative materials, methods and technologies. This bridge is one of 36 demonstration projects across Canada sponsored by ISIS Canada Research Network to assess the performance of FRP and the use of FOS (Fibre Optic Sensors) for structural health monitoring (SHM). The use of an SHM system is investigated for the purpose of determining the structural performance of the bridge for the various traffic loads and seismic loads carried by the bridge. This paper also describes the implementation of intelligent sensing for the remote health monitoring of the seismic strengthened pier of the Portage Creek Bridge. The two columns of the bridge pier were strengthened with GFRP (Glass Fibre Reinforced Polymer) wraps with a total thickness of 5 mm. In order to monitor the response of the pier under an earthquake, eight bi-directional rosette type strain gauges and four long gauge fibre optic sensors have been attached to the outer layer of the GFRP wrap on each of the two columns as shown in Fig. 3. In addition, two 3-D Crossbow accelerometers were installed on the pier cap above the columns. A durable weatherproof aluminium box with a safety lock has been installed on the pier cap to house a remote monitoring system. The National Instrument data acquisition system facilitates the remote transfer of data from the instrumented bridge. Through cable modem, the recorded data are transferred to the engineer's office. The data collected so far have proved the reliability of the instrumentation system.

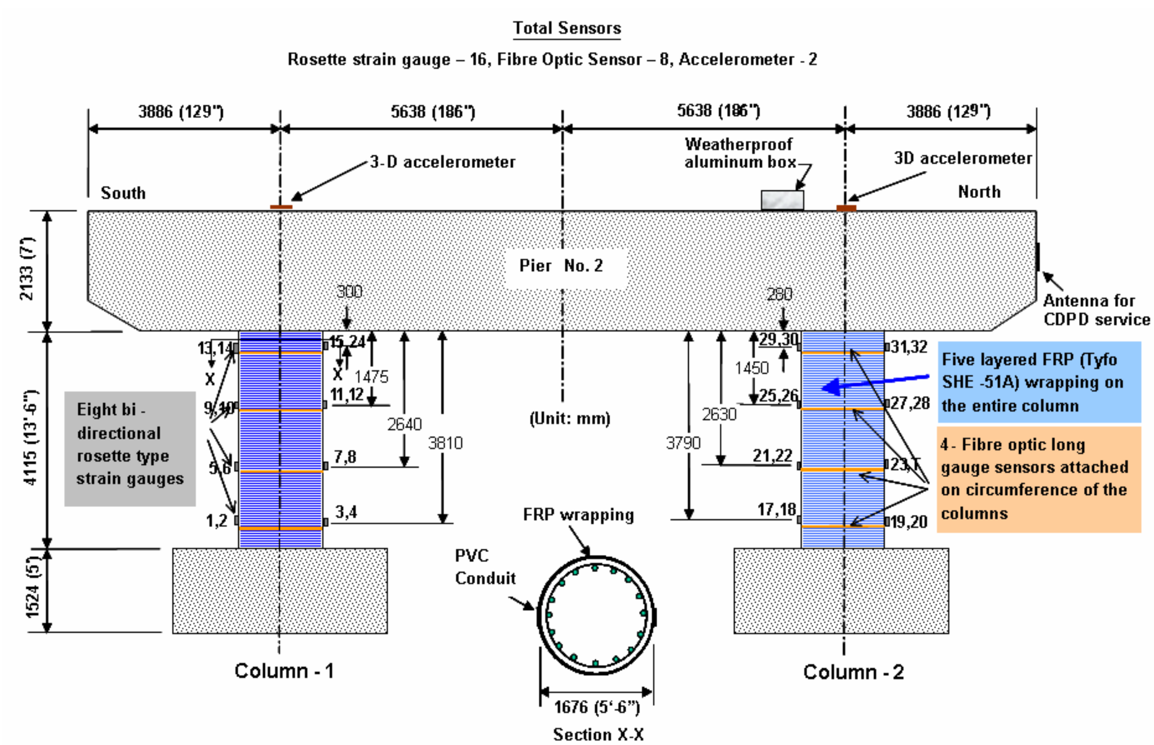


Figure 3. Elevation of Pier No. 2 (short columns) with sensor locations.

This project assesses the performance of FRP for seismic strengthening. Data from various sensors as discussed earlier are integrated into the SHM system to determine the structural performance under in-service conditions, diagnose faults, and quantify the risk of failure. Seismic strengthening with FRP is an effective and economical method of retrofitting for improved ductility and shear capacity of existing reinforced concrete columns. The seismic strengthening and instrumentation for remote monitoring was done in collaboration with the bridge consultant, Sargent and Vaughan Engineering Ltd., Victoria, and the bridge owner, the BC Ministry of Transportation. ISIS Canada assisted with the retrofit involving GFRP wraps to strengthen the short columns. The remote monitoring system provides current sensor status, and downloads measured data for analysis. It also issues a warning when the allowable limit is exceeded.

Seismic Evaluation and Design of the Retrofit System

The finite element (FE) analysis was initially conducted to determine the natural frequencies of the vibrations and corresponding mode shapes of the as-built structure. The moment demands calculated in the SAP 2000 model were amplified for P-Delta effects. Both nonlinear static pushover and response spectrum analyses were performed using the model shown in Fig. 4. Caltrans (1992) suggests that it is necessary to include enough modes of vibration to achieve a total mass participation of not less that 90% for a given bridge (CAN/CSA-S6-00, 2005 also suggests a similar approach). For a 25-mode combination used for this model, the total mass participation was 96% in the longitudinal direction and 98.5% in the transverse direction. The first two modes dominated the longitudinal response of the bridge, with periods ranging from 0.44 to 0.48 s, and a total mass participation of 79%. Transversely, the fifth mode was dominant, with a period of 0.33 s, and mass participation of 73%. Although there are no measured values of the frequencies of the as-built structure to compare with those from the FE model, the data from the accelerometers installed after the rehabilitation suggest similar values of the periods associated with the longitudinal and transverse modes. A simple cantilever model of the columns (considering only the column stiffness and an equivalent lumped mass at the top) also gives a period in the same range (0.46 s). The non-linear behaviour of the bridge was analyzed by SAP 2000, defining plastic hinges in piers, pier caps, longitudinal girders, cross beams and braces. The program also allowed for default hinge properties based on ATC-40 (1996) and FEMA-273 (1997) criteria. Normal moment capacities of the concrete columns were computed based on a compressive maximum strain of 0.003 and a compressive strength of 30 MPa. The nominal moment capacities were obtained from the interaction diagrams considering biaxial bending and applied axial loads. Nominal shear capacities of the columns were calculated using the Caltrans method (Caltrans, 1992; Priestley *et al.*, 1992). The elastic demand (D) and capacity (C) in the columns of Pier 2 for a load combination of (30% L + 100% T) were computed and the D/C ratio for shear was found to be approximately 0.80. However, on closer scrutiny, it was noticed that once plastic hinges form at the columns for Pier No. 1, a redistribution of internal forces cause greater shear forces to be resisted by the columns at Pier No. 2. This potentially increases the D/C ratio for shear to greater than 1.0. Furthermore, the pushover analysis showed that, prior to forming a plastic hinge, the columns of Pier No. 2 would fail in shear. This mode of failure has the potential to be catastrophic in nature.

In order to increase the shear capacity of the columns at Pier No. 2 to prevent catastrophic shear failure without increasing the moment capacity, the application of FRP wraps to the columns was recommended. Based on the results of the seismic evaluation of the as-built structure, it was determined that FRP wrapping should be designed to upgrade the capacity-to-demand ratios to 1.75 for the columns at Pier No. 2. In view of the column geometry (*i.e.*, a relatively short column with H/D = 2.45, where H is the height and D is the diameter of the column), a uniform circumferential wrapping was recommended. That is, the same number of layers of FRP wraps should be applied on the entire height of the column. Unidirectional FRP sheet/fabric systems were recommended with the primary fibres orientated circumferentially (i.e., at 90° to the column axis). The FRP wrapping system was designed using the methods provided in Priestley, Seible and Chai, (1992). An FRP wrapping system is usually designed for a required strength, and the properties supplied by the supplier are generally reliable. The results of these calculations are summarized in Table 1. As observed from Table 1, the modulus of elasticity of FRP materials can vary from about 30 GPa for Glass-FRP to about 300 GPa for Carbon-FRP. The ultimate tensile strain varies between 1 to 2% for CFRP and 3 to 4% for GFRP. Among the alternatives suggested in Table 1, five layers of SHE 51 GFRP wrapping system were selected for strengthening the columns of Pier 2. The FRP wrapping scheme is illustrated in Fig. 3.

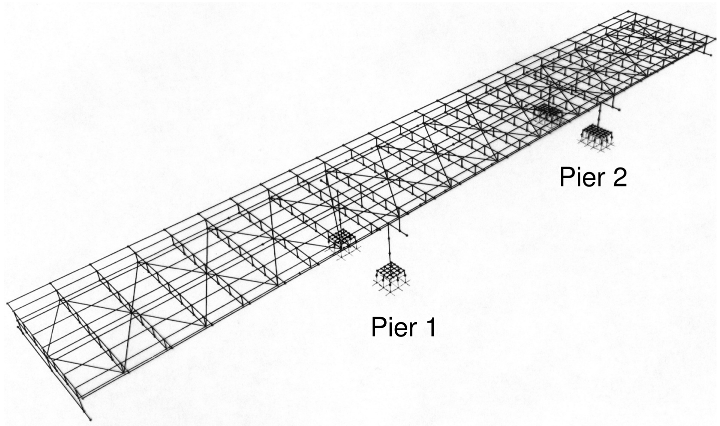


Figure 4. Finite element model of the Portage Creek Bridge.

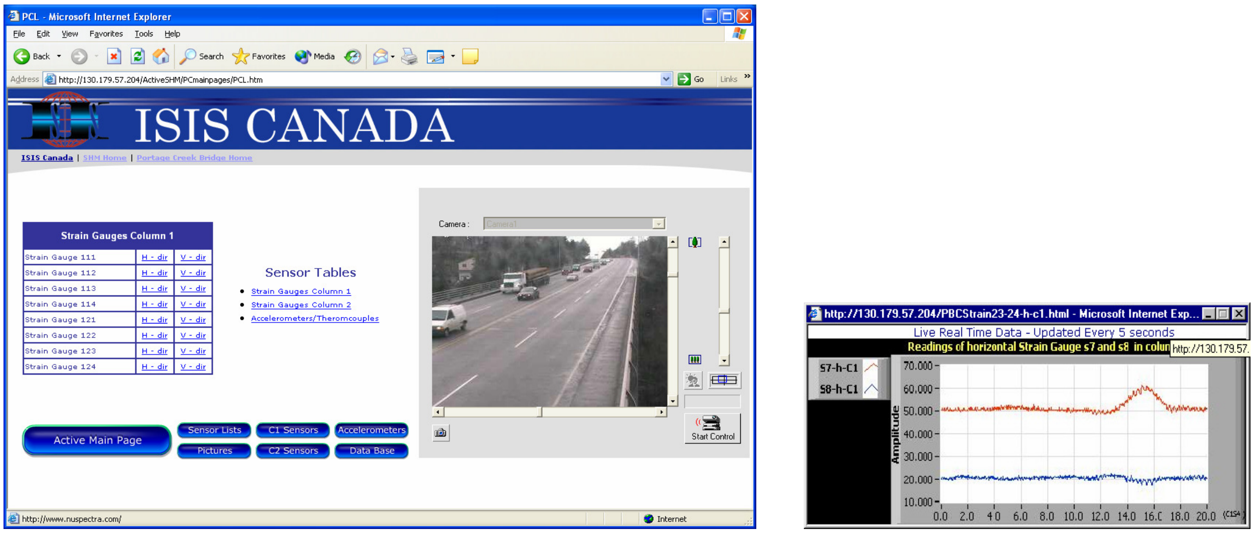
Table 1. Technical data for FRP strengthening and required number of layers.

System	Distributor	Thickness per layer (mm)	Tensile Strength (MPa)	Modulus (GPa)	No. of layers
SHE 51 / TYFO S	Composite Retrofit Int'l / Fyfe Co.	1.3	552	27.6	5
Sika Wrap Hex 100G	Sika Canada Inc.	1.0	600	26.1	7
MBrace CF 130 MBrace CF 530 MBrace EG 900	Master Builders Inc.	0.165 0.165 0.353	3480 2940 1730	227 372 88	5 3 6
Replark Type 30 Replark Type MM	Mitsubishi Chemical Corporation	0.167 0.165	3400 2900	230 390	5 3

Instrumentation for Remote Monitoring

An elevation view of the instrumented Pier No. 2 is shown in Fig. 3 with sensor locations. Initially, a telephone line was installed to send data from the site to the central server. Later, a high speed internet connection was installed and a continuous data feed was established to the ISIS Canada web site. The bridge can now be remotely monitored from anywhere. A traffic camera was also installed to synchronize the traffic picture with the strain data. A thick-walled lockable and weatherproof aluminum box installed on the pier cap houses all necessary instruments and connecting cables. The BC Ministry of Transportation has installed a power supply outlet, and the cables and wires are protected with PVC conduits and junction boxes. As shown in Fig. 3, the accelerometers were placed on the pier-head as the centre of mass of the bridge deck and the pier-head is close to this position. The actual centre of mass is at a higher elevation where the accelerometer can not be placed due to practical constraints. The current location provides accessibility to the accelerometers and proximity to the data logger, which is placed on the pier-head. An onboard computer is also connected to the data logger in order to connect to the internet and to manage it remotely. Two accelerometers on the pier-head over each column are sufficient to capture the lateral vibration characteristics of the retrofitted columns and also to provide additional information about the torsional effects of the deck on the columns.

The web page for Portage Creek Bridge real time monitoring is hosted by a centralized SHM system under www.isiscanada.com. The individual page for Portage Creek Bridge SHM system is designed with the same framework as for the other SHM systems and can be easily reused for new SHM systems on different projects. Fig. 5(a) shows the internet web-page for Portage Creek Bridge. A Pan, tilt, zoom web camera is installed on-site and integrated into the web page to allow the user to view the condition of the structure in real time. The simultaneous display of web camera images and sensing data has been adopted for this site. A user can pick up and access individual sensor's data from the sensors list. A pop up window will display and update the sensor’s readings every 5 seconds. Processed data, such as the FFT analysis, are also updated every 5 seconds and published on the web page. A sample of strain gauges' output is displayed in Fig. 5(b). Similar plots, not shown here, can be produced for accelerometer and the estimate of natural frequency can be obtained from the Fourier analysis of the accelerometers data. Fig. 5(b) shows that the vertical strain does not change appreciably due to normal traffic loads (the hump in one of the strain gauge output indicates a heavy truck passing over the bridge).



(a) (b)

Figure 5. (a) Web-iteractive page for online monitoring of the Portage Creek Birdge, (b) a typical output from a strain gauge installed in the bridge coulmns.

Periodic Tests for the Monitoring System

Physical conditions of the onsite equipment and the monitoring system are inspected and tested from time to time. An inspection in August, 2004 determined that the accelerometers and strain gauges were functioning properly. The long gauge fibre optic sensors were not connected to the online monitoring system due to a technical problem associated with the data interrogation system. One of the long gauge sensors was known to be damaged during installation, but the other seven appeared to be active. However, the data obtained from them could not be processed due to the mismatch between the gauge length of the sensors and the data interrogation system. This problem was again detected during the static and dynamic load tests conducted in May, 2005. This was corrected later and the performance of the long gauge FOS was tested in September, 2005.

In May, 2005, static and dynamic tests were conducted on Portage Creek Bridge. The 26 ton load test vehicle was positioned over each instrumented column for a period of time. During this period, the readings from the electrical strain gauges were observed. Afterwards, dynamic tests were conducted at a speed of 20 kmph over each column. The increase in static and dynamic strains was found to be fairly low (within 10 microstrain) indicating excellent service condition.

Fig. 6 shows the incremental strain in two of the strain gauges in Column 2 during the static load test. Strain gauge 4-1 experienced an increase of approximately 6 microstrain, while strain gauge 6-1 records an increase of approximately 9 microstrain. Strain gauges 4-1 and 6-1 correspond to Sensors 23 and 27, respectively, in Fig. 3. Both strain gauges were positioned vertically on the column. It should be noted that traffic flow existed on the other lanes during the static test. Therefore, small changes of strain are seen in the strain gauge readings. The corresponding strain gauges in Column 1 (5 and 9, respectively) register a similar level of increase in strain when the test truck is placed over that column. It is clear from the test that the 26 T load does not increase the axial strain in the columns appreciably. Similar results are obtained from the dynamic test.

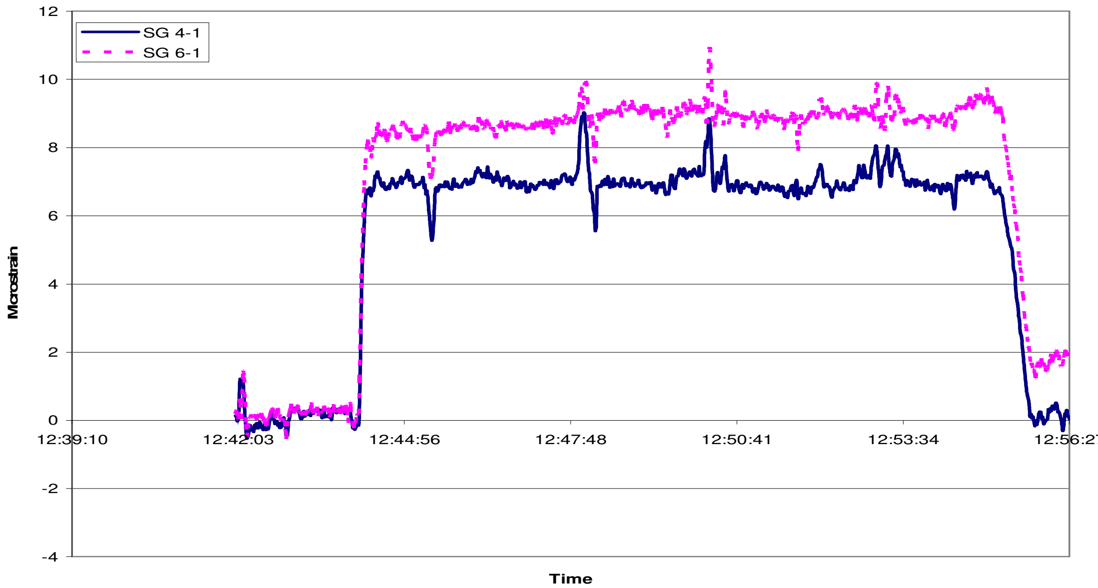


Figure 6. Increase in strain in Column 2 during the static load test.

A plot of the change in hoop displacements for three long gauge fibre optic sensors in Column 2 is shown in Fig. 7 from the time of instrument start-up. It must be noted that the strain values are stabilized after the initial warm-up period, which is rather long (about an hour), typical of the particular type of the data interrogation system. Detailed working principles of these sensors are explained in Tennyson *et al.* (2006). The data peaks show the response due to vehicle traffic. The purpose of the sensors is to monitor the FRP bond integrity to ensure sufficient column strength exists to accommodate seismic loading conditions. It is concluded that the FRP is well bonded to the concrete columns since no abnormal strains (*e.g.*, unusual difference in Hoop stress in FRP at various levels of the strengthened columns) were detected.

Data Management

Real-time access to the data generated from an SHM system is a key step in developing effective structural health monitoring systems. How to organize and manage the data, turn the data into knowledge and knowledge into decisions is not only a complex task, but also a significant part of an SHM system. Another important step is to identify which part of the data does not follow a regular pattern. Such unusual data need to be analyzed and the events that may produce such data must be identified. One of the simplest techniques to detect such unusual or novel events from the data is to check against an established threshold based on past history of the data. If the data points lie beyond the threshold, it would be regarded as those corresponding to an unusual event experienced by the structure. However, such simplistic methods may not work on a long term basis, and when there are a number of gauges and sensors involved, establishing a realistic threshold for the system is often difficult.

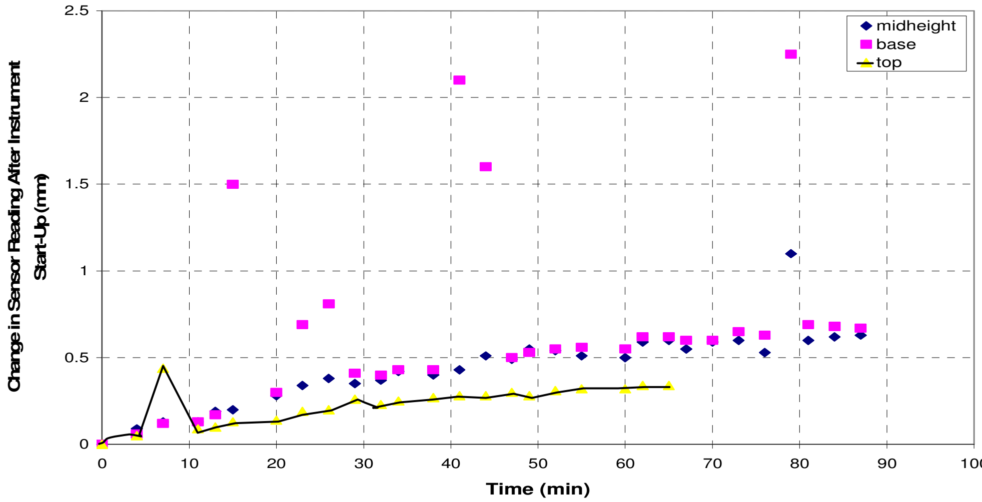


Figure 7. Response of the long gauge fibre optic sensors during instrument startup.

Card and McNeil (2004) have developed an intelligent system to determine the unusual or novelty events occurring in the SHM data. Based on the inputs from the sensors' readings, a trained neural network will learn and synthesize the patterns in the sensor data corresponding to the normal operating conditions and behaviour of the structure. Data corresponding to an unusual event would not follow the usual pattern recognized by the neural network, and a flag would be raised to indicate the novel event. In the current implementation, the novelty event detection algorithm is applied to every 5 seconds window of data to filter out usual or mundane data representing normal behaviour of the structure and the novelty data representing unusual behaviour of the structure would be used for further processing.

One of the advantages of the novelty events detection system is that the mundane data, which constitute the major part of the SHM data could be isolated and discarded, while only the novelty data could be stored in a database for further analysis. This would drastically reduce the demand on data storage space. Some novelty event detection experiments are carried out based on the data collected from Portage Creek Bridge. The novelty detection algorithm compares the difference between the data pattern that has been learned and synthesized by the neural network, and the incoming data for testing. Based on this comparison, the algorithm calculates a novelty parameter or metric as explained in Card and McNeil (2004). When the novelty metric is high, the event is marked as unusual. Fig. 8(a) shows the result of novelty event detection for a novelty event that happened on August 2, 2003, in Portage Creek Bridge, while Fig. 8(b) shows the jump in the strain gauge readings. According to the data analysis, this novelty event only lasted for 60 seconds then all the strain gauge readings went back to normal. From current data analysis, the bridge is still functioning in normal condition. Sensors in the columns of Pier 2 are expected to capture the deformation in the columns due to ground motion, while they would remain relatively quiet under vehicular traffic on the bridge. One of the goals of the monitoring program is to identify the dates and times from the sensor data whenever noticeable ground shaking occurs. These dates and times would then be correlated to the corresponding ground motion records, if available.

It is clear from Fig. 8 that the detection of such events from sensor data is now possible using the novelty detection technique as explained earlier. However, as of now, correlation of the novel events with the ground motion records has not been performed since the novel event detection technique has only been tested for a small window of data covering July 31, 2003 to September 15, 2003, and the novel event identified during that period perhaps corresponds to a minor ground motion for which no records are available. As the database is updated with the full range of sensor data covering the entire span of the monitoring program to date, all major and minor ground motion events in that period will be detected and correlated. At that point, it would also be possible to study the response characteristics of the bridge corresponding to various levels of ground motion and identify changes in structural stiffness due to damage or other significant events. The novel event as identified in Fig. 8 indicates that the maximum strain of 413 microstrain occurs in the vertical direction at the base of Column 1. The corresponding strain at the opposite face of the column is recorded as -34 microstrain. The strains at these points, recorded at a quiet period when traffic is low and strain gauge readings are stable, are close to 186 microstrain and -12 microstrain, respectively. This means that the novel event detected here could be produced by the combination of live load and ground motion in horizontal and vertical directions. A clearer picture will emerge when sensor data for longer span of time is processed and other novel events are identified and analyzed along with the available ground motion records.

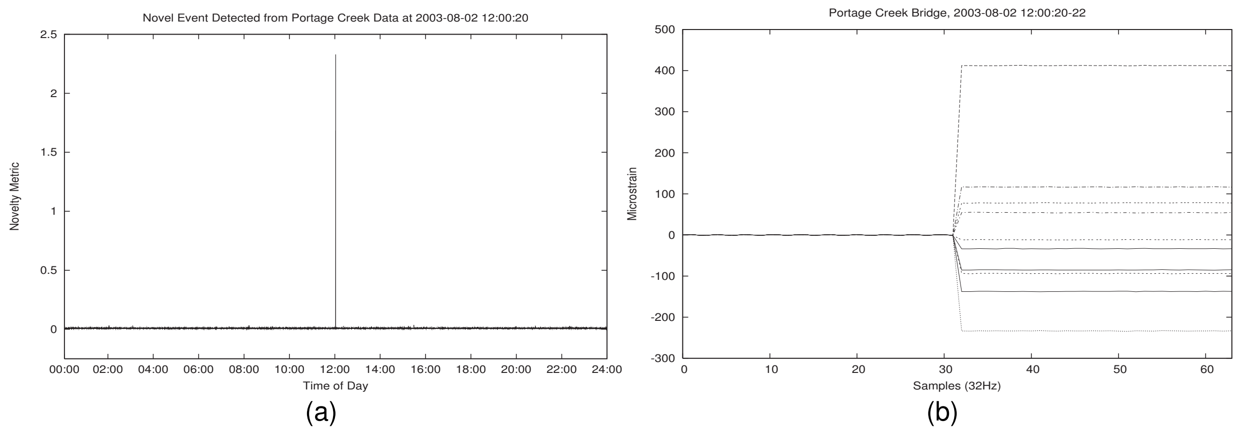


Figure 8. Novelty event detection in Portage Creek Bridge SHM System, (a) novelty metric, and (b) sensor data corresponding to the novelty event.

Discussion and Conclusions

The paper presents the details of seismic retrofit and monitoring of the Portage Bridge columns. The work presented here is summarized below along with some concluding remarks.

- The bridge was designed using an earlier bridge design code and needed to be upgraded to conform to the seismic guidelines of a more recent code. A glass fibre reinforced polymer wrap system was designed and implemented for a pair of columns in one of the bridge piers that were found to be vulnerable.
- Seismic strengthening with FRP is an effective and economical method of retrofitting for improvement in ductility and base shear resistance of existing structures. Designing bridges for seismic resistance and monitoring has become a priority in areas of moderate to high seismicity. The instrumentation for the Portage Creek Bridge columns is an early attempt to build a model smart bridge for continuous remote monitoring.
- A number of electrical strain gauges, long gauge fibre optic sensors and accelerometers, and a digital video camera were installed at the time of the retrofitting action. An integrated structural health monitoring system was developed that enabled the monitoring data to be collected and transported over the internet and stored in a central server to facilitate web-based monitoring.
- The integration mechanism and web-based monitoring schemes are working as expected. Fibre optic sensors (FOS) integrated with strain gauges and accelerometers are used for structural health monitoring (SHM) remotely.
- Measured data from the various sensors that are integrated into the SHM system is meant to provide information to determine the structural performance under in-service conditions, diagnose faults, and quantify the risk of failure. The project described herein takes some steps in that direction.
- The preliminary analysis of the monitoring data and field tests suggest that the axial strain in the columns do not change appreciably during the normal operation of the bridge, which indicates that the retrofitted bridge is performing very well.
- The Hoop displacements determined by the long gauge sensors are also low. The data from the long gauge FOS shows that the FRP wraps are bonded well to the concrete columns.

- Interpretation of the monitoring data and isolating the unusual or novel events are important for effective monitoring. A neural networks-based novel events identification technique has been used to isolate the unusual events in the case of Portage Bridge.
- The monitoring system was developed to capture the response of the retrofitted columns under seismic events. So far no strong motion event has occurred. Thus, the monitoring data lack highly unusual patterns. Some events detected by the algorithm as unusual are perhaps due to minor ground tremor as they are not associated with any unusual traffic condition and the sensor data fall back to the usual pattern afterwards.
- The automated analysis of data and structured interpretation in the cases of future unusual events would certainly provide valuable insight on the behaviour of the structure, the performance of the retrofit system, provide guidance to the design of better monitoring systems for other structures.

Acknowledgments

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