



GFRP SEISMIC STRENGTHENING AND STRUCTURAL HEALTH MONITORING OF PORTAGE CREEK BRIDGE CONCRETE COLUMNS

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SUMMARY

Located in Victoria, BC, Canada, the Portage Creek Bridge is a 125m long, three-span structure with a reinforced concrete deck supported on two reinforced concrete piers, and abutments on H piles. The bridge was designed prior to the introduction of current bridge seismic design codes and construction practices. Therefore, it was not designed to resist the earthquake forces that are required by today's standards. The bridge is on a route classified as a Municipal Disaster Route scheduled to be retrofitted to prevent collapse during a design seismic event, with a return period of 475 years.

Conventional materials and methods were used to retrofit most of the bridge. The dynamic analysis of the bridge predicted the two tall columns of Pier No. 1 will form plastic hinges under an earthquake resulting in additional shear to the short columns of Pier No. 2. A non-linear static pushover analysis indicated that the short columns will not be able to form plastic hinges prior to failure in shear. The innovative solution of Fibre Reinforced Polymer Wraps (FRPs) was chosen to strengthen the short columns for shear without increasing the moment capacity.

The FRP Wraps and the bridge were instrumented as one of 36 demonstration projects across Canada sponsored by ISIS Canada to assess the performance of FRP and the use of FOS (Fibre Optic Sensors) for structural health monitoring (SHM). The two columns of the bridge pier were strengthened with GFRP (Glass Fiber Reinforced Polymer) wraps 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.

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The data is collected through high speed internet line to an interactive web page at ISIS Canada's web site. The bridge can now be monitored from anywhere. The data collected so far has proved the reliability of the instrumentation system.

INTRODUCTION

This paper describes an innovative way of seismic strengthening and remote structural health monitoring for a Disaster-Route bridge in British Columbia, Canada. In 1982, the BC Ministry of Transportation designed the Portage Creek Bridge, as shown in Figure 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 125m (410ft) long, three-span structure with a reinforced concrete deck supported on two reinforced concrete piers, and abutments on H piles (Figure 2). The deck has a roadway width of 16m (52ft) with two 1.78m (6'6") sidewalks and aluminum railings (Figure 3). The bridge was designed prior to the introduction of current bridge seismic design codes and construction practices. Therefore, it was not designed to resist the earthquake forces that are required by today's standards (FHWA [1]). It does appear, however, that consideration was given to some seismic aspects, as evidenced by a review of the drawing details. The bridge is classified as a Disaster Route bridge and was to be retrofitted to prevent collapse during a design seismic event, with a return period of 475 years.



Fig. 1 Portage Creek Bridge in Victoria, British Columbia

Conventional materials and methods are being used to retrofit most of the bridge. The dynamic analysis of the bridge predicts the two tall columns of Pier No. 1 will form plastic hinges under an earthquake. Once these hinges form, the short columns of Pier No. 2 will attract additional shear. A non-linear static pushover analysis indicates that the short columns will 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. This paper will describe the methodology and techniques that were used to strengthen the Portage Creek Bridge.

This bridge is one of 36 demonstration projects across Canada sponsored by ISIS Canada to assess the performance of FRP and the use of FOS (Fibre Optic Sensors) for structural health monitoring (SHM).

The use of a 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 Fiber 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 the Figure 4. In addition, two 3-D Crossbow accelerometers are installed on the pier cap above the columns. A durable weatherproof aluminum 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 engineer's office. The data collected so far has proved the reliability of the instrumentation system.

This project assesses the performance of FRP for seismic strengthening. Fibre optic sensors (FOS) integrated with strain gauges and accelerometers are being used for structural health monitoring (SHM) remotely. Measured data from the various sensors that are integrated into the SHM system 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 improvement in ductility and base shear resistance of existing structures. 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. Using its innovative technology, 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 via wireless transmission. It also issues a warning when the allowable limit is exceeded. This paper discusses a novel approach using smart sensors and wireless communication technology to monitor the health of large civil structures remotely.

SEISMIC ANALYSIS AS-BUILT AND RETROFIT ELASTIC ANALYSIS

The Portage Creek Bridge was modeled in 3-dimensions using SAP 2000 for "as-built" conditions. Conventional dynamic modal elastic response analysis, using the standard AASHTO [2] response spectra with $A=0.35$ g, was then performed to establish the force demands of bridge members and the displacement of the bridge. The seismic force demand on all members was determined by assuming that all structural members would remain elastic and uncracked. By using the uncracked section properties, the structure generally responds in shorter natural periods, resulting in higher seismic forces in all bridge members.

The slab was modeled using shell elements. The remainder of the bridge was modeled as a space frame with 2-node beam elements. The Caltrans recommended approach is to include enough modes of vibration to achieve a total mass participation of not less than 90% for a given bridge. 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%.

Finite Element Model for Earthquake Analysis

As indicated previously, the bridge was modeled for the finite element program SAP 2000. The geometry of the bridge was simplified as shown in Figures 2 and 3. The standard steel sections were defined and

specified directly into the program. The concrete sections of the footings, column piers and pier caps were defined exactly as specified in the drawings.

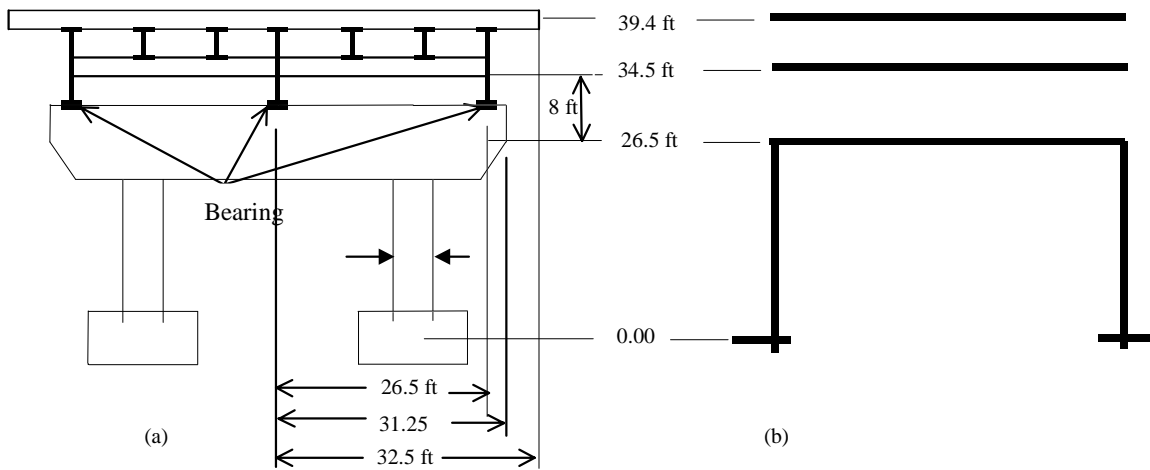


Fig. 2(a) Portage Creek Bridge (McKenzie overpass) / Fig. 2(b) simplified geometry of Pier No. 1

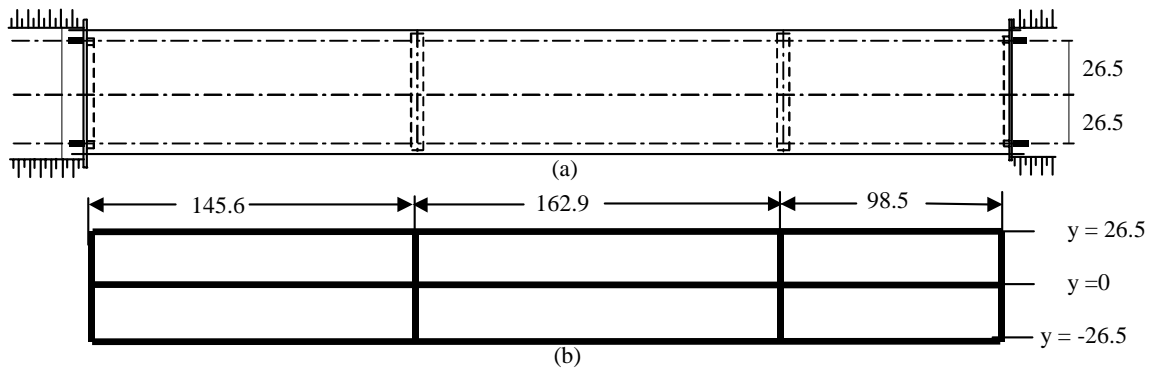


Fig. 3(a) Plan of Portage Creek Bridge / Fig. 3(b) simplified bridge geometry

The finite element model is shown in Figure 4. The details of the sections were either calculated or selected from the AISC table provided by the SAP 2000 library of tables. The finite element analysis was initially conducted to determine the natural frequencies of the vibrations and corresponding mode shapes. The forces shown are at the abutments and piers. The moment demands calculated in the SAP 2000 model were amplified for P-Delta effects. Both dead loads and response spectrum analysis were performed using the model described above.

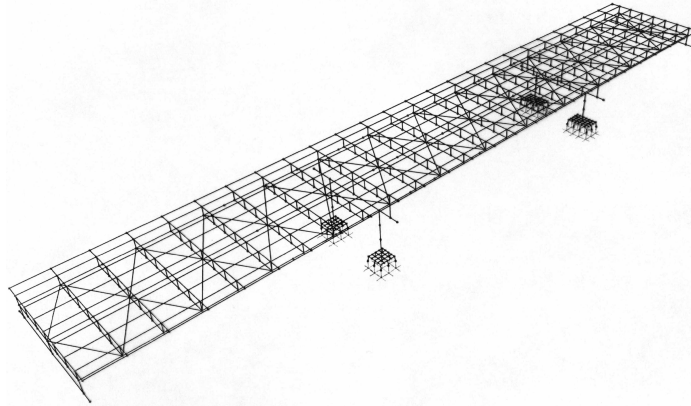


Fig. 4 Finite element model of the Portage Creek Bridge

Non-linear Static Pushover Analysis

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 [3] and FEMA-273 [4] criteria.

The pushover analysis consists of three load cases. Push 1 was gravity load; Push 2 was a continuation of Push 1 with a choice of the mode that created maximum transverse forces. The push was applied at the centre of the superstructure of the bridge in the transverse direction. Maximum deflection was chosen to give the total collapse of the bridge. Push 3 was similar to Push 2 but the mode that excited the bridge longitudinally was selected and push was applied at the end support longitudinally. In all the load cases P-Delta was included.

Non-linear static pushover analysis involves a general sequence of steps:

- a) Use the model that was idealized for the response spectrum analysis.
- b) Define pushover cases as described above.
- c) Define hinge properties and assign these to frame elements.
- d) Run the pushover analysis.
- e) Review the pushover analysis results.

Demand/Capacity (D/C) Ratio Determination

Capacity Calculation

Normal moment capacities of the columns were computed based on a compressive maximum strain of 0.003 and a compressive strength of 30 MPa. Capacities were calculated by hand, or by SAP 2000 with spot-checking by hand. 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, which is presented in Caltrans *Memo to Designers Change letter 02 of March 1995* [5]. Other methods including ACI/AASHTO shear design equations, the University of California at San Diego proposed model, and the University of California at Berkeley proposed model were also investigated for comparison.

Pier No. 2 Columns

Elastic D/C ratios for shear of approximately 0.80 give the impression of adequate reserve. However, on closer scrutiny, it was noticed that once plastic hinges form at the columns for Pier No. 1, a redistribution

of forces cause greater shear forces to be resisted by the columns at Pier No. 2. This potentially increases the D/C ratios for shear to greater than 1.0 as shown in Table 1. Furthermore, the pushover analysis shows that, prior to forming a plastic hinge, the columns of Pier No. 2 will fail in shear. This mode of failure has the potential to be catastrophic in nature.

Table 1 Portage Creek Bridge D/C Ratios

Location	Combo	Axial demand P (kips)	Longitudinal shear demand V ₂ (kips)	Transverse shear demand V ₃ (kips)	Result Shear demand V _d (kips)	Shear Capacity V _n (kips)	C / D
TOP	30L + 100T	745	54	914	916	1145	1.25
BOT	30L + 100T	793	59	932	934	1149	1.23
		Axial demand P (kips)	Transverse Flexural demand M ₂ (kips*ft)	Longitudinal Flexural demand M ₃ (kips*ft)	Resultant Flexural demand M _d (kips*ft)	Flexural capacity M _n (kips*ft)	D / C
TOP	30L + 100T	1317	5458	283	5465	8829	1.62
BOT	30L + 100T	1365	7081	933	7142	8070	1.13

Retrofit Measures

Pier No. 2 Column

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.

FRP WRAPS FOR STRENGTHENING

Using Table 1, the FRP wrapping should be designed to upgrade these capacity-to-demand ratios to 1.75. The required shear capacities are thus:

$$V_{aj} = 916 \times 1.75 = 1603 \text{ kips (top)}$$

$$= 934 \times 1.75 = 1635 \text{ kips (bottom)}$$

The shear capacity shortfalls, to be provided by the FRP wrapping are:

$$V_{aj} = 458 \text{ kips (top)}$$

$$= 486 \text{ kips (bottom)}$$

Design of the FRP Wrapping Configuration

In view of the column geometry (i.e.: a relatively short column with H/D = 2.45), a uniform circumferential wrapping is 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 are recommended with the primary fibres orientated circumferentially (i.e., at 90° to the column axis). The design shear enhancement to be provided by the FRP wrap is:

$$\Phi_s V_{aj} = 486 \text{ kips} = 2160 \text{ kN}$$

where the shear capacity / reduction factor $\Phi_s = 0.85$ (Priestly [6]).

The design approach is based on the methods described by Priestly et al [6]. Accordingly,

$$V_{aj} = 2.25 t_f f_j D$$

$$\text{where } f_j = 0.004 E_j \leq 0.75 f_{uj}$$

In these equations, t_f is the thickness of the FRP wrap, f_j is the effective stress provided by the wrap, D is the column diameter, E_j is the elastic modulus of the FRP in the fibre direction, and f_{uj} is its corresponding ultimate tensile strength. Based on these equations and the material technical data presented in the brochures of the suppliers of various commercial FRP wrapping systems, the required number of layers for each system has been calculated to ensure a minimum $\Phi_s V_{aj} = 2160 \text{ kN}$. The results of these calculations are summarized in Table 2. The FRP wrapping scheme is illustrated in Figure 5.

Table 2 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	Master Builders Inc.	0.165	3480	227	5
MBrace CF 530		0.165	2940	372	3
MBrace EG 900		0.353	1730	88	6
Replark Type 30	Mitsubishi Chemical Corporation	0.167	3400	230	5
Replark Type MM		0.165	2900	390	3

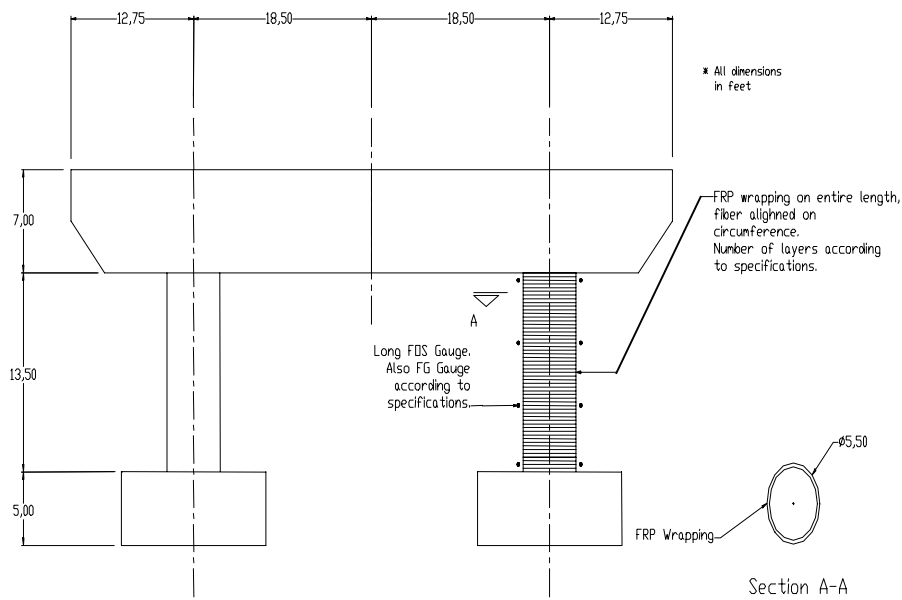


Fig. 5 FRP Wrapping Scheme

Typical specifications for the preparation of the concrete surface, installation of the FRP, quality control and maintenance are given in Neale [7].

INSTRUMENTATION FOR REMOTE MONITORING

ISIS Canada has made significant progress in the past seven years in the field of remote monitoring. Conventional sensors along with fibre optic sensors enhance the accuracy of the measurement factors. The following sensors were installed in the Portage Creek Bridge for remote structural health monitoring Mufti et al [8]:

- Eight bi-directional strain gauge rosettes on each column
- Four long gauge fibre optic sensors on each column
- One 3-D accelerometer on top of the pier cap of each column

An elevation view of the instrumented Pier No. 2 is shown in Figure 6 with sensor locations. Initially, eight Data Dolphin Data Loggers (Optimum Instruments Inc. [9]) each with four precision channels were installed as a multi-drop unit to collect strain data from the sensors. Optimum Instruments Inc. who supplied the data loggers was, unfortunately, unable to adapt their system to the accelerometers and fibre optic long gauges. Other limitations of the system were:

- Limited data storage capacity
- Minimum data record interval of 10 seconds which is inadequate for dynamic events such as earthquakes
- Only one data logger can be connected at a time, so only four channels of data can be viewed at a time
- Significant download burden and system down time

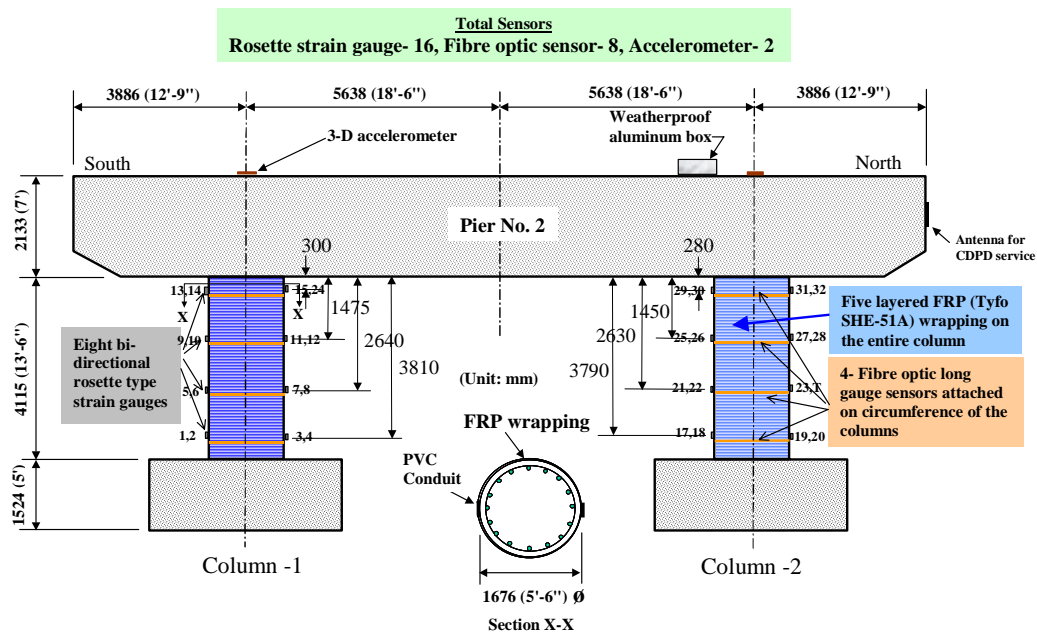


Fig. 6 Elevation of Pier No. 2 with sensor locations

In order to overcome the limitations, first a telephone line was installed and then ultimately the data loggers were changed to NSI loggers. A high speed internet line was installed from Shaw Cable Co. and a continuous data feed was established to the ISIS Canada web site. The bridge can now be monitored from anywhere.

A traffic camera has also been installed to synchronize the traffic picture with the stain data. A thick-walled lockable and weatherproof aluminum box houses all necessary instruments and connecting cables. The box is 450 (18") × 440 (17.5") × 1400 (56") mm (width × height × length) and sits on the north end of the pier cap. The BC Ministry of Transportation has installed a power supply outlet, and the cables and wires are protected with PVC conduits and junction boxes.

Sensor Description and Installation

A 25 mm wide band along the periphery of the column at four levels was rubbed clean and all traces of dust removed. As is demonstrated in Figure 6, five-layers of FRP wrap were applied and allowed to harden. Then strain gauges and fibre optic sensors were attached to the outer surface of the wrap.

Fibre Optic Sensors

Fibre optic long gauge sensors developed by Fox-Tek Inc., Toronto, (Tennyson [10]) in collaboration with ISIS Canada were installed on the bridge. The long gauge system measures path displacement between two points on the structure by means of two mirrors formed on a fibre optic lead. This system works on the principle of low coherence interferometry using a light emitting diode. The light from the diode is split in two, travels two different path lengths and is then recombined at a photo detector. The measurement obtained is the total displacement over the gauge length of the sensor. First, a smooth surface was prepared by wiping with alcohol to remove all impurities. The sensor coil was gradually opened and taped to the prepared surface on the column. M-Bond adhesive with epoxy resin was used to bond the sensor to the FRP wrapping at predetermined locations.

Strain Gauge Rosettes

A strain gauge rosette is an arrangement of two or more closely positioned gauge grids, separately oriented to measure normal strains along different directions. Two element 90° Micro-Measurements CEA-Series strain gauges of 350Ω resistance were installed on each column, as shown in Figure 6. A special clamping system was devised to ensure proper bonding between the FRP and the sensors. The device was comprised of a steel wire rope, turnbuckles and wooden pressure pads. The wire was wound around the column. After the gauge was bonded to the column surface, the pressure pad was placed on the top of the gauge and the clamping pressure was applied with turnbuckles. Each strain gauge came with two pairs of 20 mm long pre-soldered short lead wires and sufficient extension wires.

Accelerometers

M Series Cross Bow 3-D accelerometers were selected for this installation. The M Series sensing element is a silicon micro-machined capacitive beam that is extremely small in die area and rugged. The capacitive beam is held in force balance for full-scale non-linearity of less than 0.2%. The M Series accelerometer operates on a single +5 Vdc power supply. Aluminum base plates were glued to the center of the columns at the top of the pier cap concrete surface. The accelerometer and cables were covered with a junction box and connected to the main conduit through a PVC pipe.

DATA ACQUISITION AND REMOTE COMMUNICATION

Data Acquisition

The Data Acquisition System is PC-based and equipped with National Instrument SCXI signal conditioning system and a NI A/D card (see Figure 7). The sensing signals are noise compressed and amplified by the signal conditioning system and multiscanned by the A/D card. A LabVIEW application program is continuously running on the PC as a data collector and publisher. The data is collected at a rate of 32Hz and published to the data socket server every 5 seconds. The data socket server is located in the on-site PC and has the same IP address as the publisher.

On the central control site, the data server is a Dell SC1400 Windows 2000 server. A LabVIEW application program is running continuously to subscribe the data from the publisher. Every 5 seconds the new data is transferred and real time signal processing is applied to the data. FFT is implemented to analyse the output from the accelerometers. The data server generates a data file every day for this monitored structure.

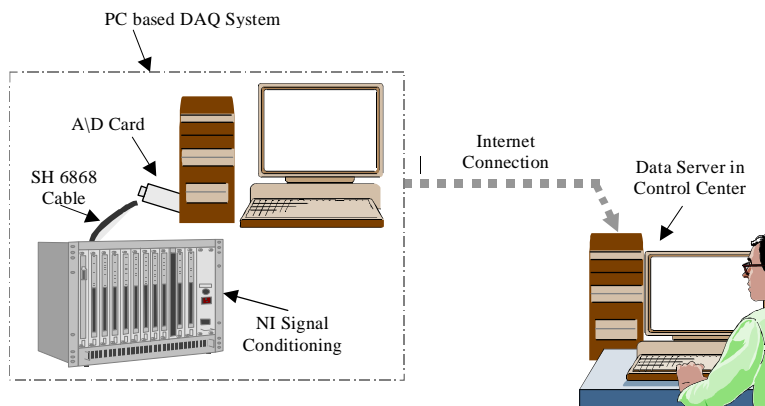


Fig. 7 Diagram of the Data Acquisition and Remote Communication

Internet Cable Connection

CDPD (Cellular Digital Packet Data) system with an IP address was installed first for remote data transfer option. However, poor coverage of the CDPD service at the bridge site and the lower data transfer rate (19.2 Kbps) was not suitable for continuous monitoring. Then, a landline was installed as a remote communication mode for the bridge site, which had a stable connection with a higher data transfer rate (57 kbps). This transfer rate was still inadequate and there was a considerable download burden in accessing the data. Finally, a high speed internet line was installed from Shaw Cable Co.

INTERACTIVE WEB PAGE

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. Figure 8

shows the 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.



Fig. 8 Portage Creek Bridge SHM web page integrating sensing data and web camera

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, is also updated every 5 seconds and published on the web page. A sample of strain gauges' output is displayed in the Figure 9.

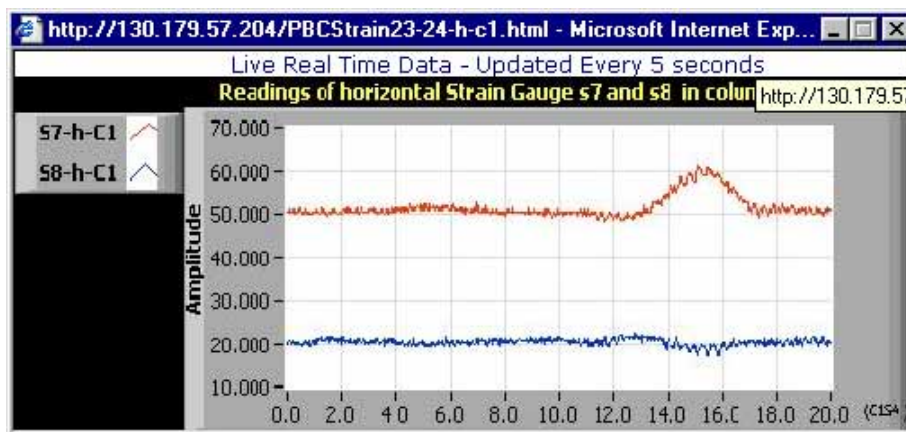
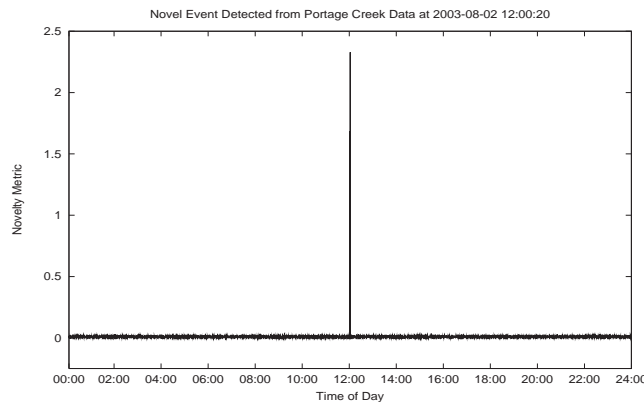


Fig. 9 Real time strain gauge readings in Portage Creek Bridge SHM System

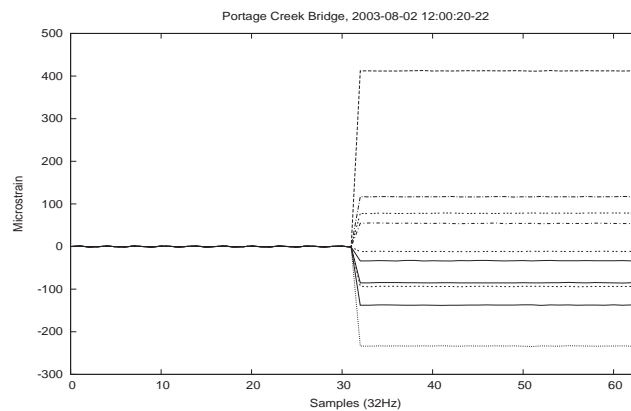
DATA MANIPULATION

Real-time access to the data generated from 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 the most complex but significant phase in SHM

Researchers at ISIS Canada are developing an intelligent system to determine the novelty events occurring in the collected data. Based on the inputs from the sensors' reading and FFT preprocessing of those readings, a trained neural network will inform civil engineers when important sensor readings are being generated or when the structure behaves abnormally. The novelty event detection algorithm will apply to every 5 seconds data to filter out mundane data and only the novelty data will be imported into the database. The database has been set up based on MySQL, the popular open source database. It has been verified that MySQL allows the data server to be more reliable, easier to access and is less costly to maintain. Some novelty event detection experiments are carried out based on the data collected from Portage Creek Bridge. Figure 10(a) shows the result of novelty event detection for a novelty event that happened on August 2, 2003, in Portage Creek Bridge, while Figure 10(b) shows the jump in the strain gauges readings. According to the data analysis, this novelty event only lasted for 60 seconds then all the strain gauges readings went back to normal. From current data analysis, the bridge is still functioning in normal condition.



10(a)



10(b)

Fig. 10 Novelty event detection in Portage Creek Bridge SHM System

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 Figure 10 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 only minor ground movements 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 in the event of damage.

At the novel event as identified here, Figure 10(b) 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.

CONCLUSION

This research project assesses the performance of FRP for seismic retrofitting. Fibre optic sensors (FOS) integrated with strain gauges and accelerometers are being used for structural health monitoring (SHM) remotely. Measured data from the various sensors that are integrated into the SHM system 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 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. Now that instrumentation for the Portage Creek Bridge Pier No. 2 has been completed, the bridge is a model smart bridge for continuous remote monitoring, another example of innovative technology by ISIS Canada.

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