Seismic and Performance Monitoring Instrumentation on the Lions Gate Bridge

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ABSTRACT

Opened to traffic in 1938, the Lions Gate Bridge is an 847m long suspension bridge with approach viaduct structures. It is one of the most well-known bridges in the British Columbia, and underwent a complete deck replacement in 2001. The suspended span bearings at the main towers failed since their installation as part of the deck replacement, and have been recently replaced. A finite element model of the suspension bridge was created to design the new bearings and determine the required loading and ranges of movement under all load conditions. The required static load cases were developed, and time-history analyses were used for the seismic load cases. Checks were performed to confirm that the responses obtained from the numerical model represented the response of the real bridge, including comparing movements and loads with those in the design drawings for the 2001 deck replacement, and comparing mode shapes obtained with measured mode shape periods from a 1975 study. Strong motion instrumentation was installed on the bridge, and the real structure mode shapes could be measured directly and compared to those obtained from the numerical model. A Structural Health Monitoring system was installed on the bridge that included displacement sensors on the new bearings, acceleration sensors and weather stations on the suspension bridge, and tilt meters on the truss. The displacement sensors on the new bearings are being used to monitor the bearings' performance in near real-time and ensure the validity of the design assumptions. This paper presents details of the failing bearing replacement as well as the details of the instrumentation and analysis procedures used to analyse the collected vibration data to calculate the design parameters, and check that the modelling methods used were sufficiently accurate to meet the project requirements.

Keywords: Seismic analysis, time-history analysis, structural health monitoring, bearing retrofit, instrumentation.

INTRODUCTION

Opened to traffic in 1938, the Lions Gate Bridge is an 847m long suspension bridge with approach viaduct structures. It is one of the most well-known bridges in British Columbia, and underwent a complete deck replacement in 2001. The suspended spans are shown in elevation in Figure 1. The suspended span bearings at the main towers failed since their installation as part of the deck replacement, and they were recently replaced with new bearings with a modified design [1, 2].

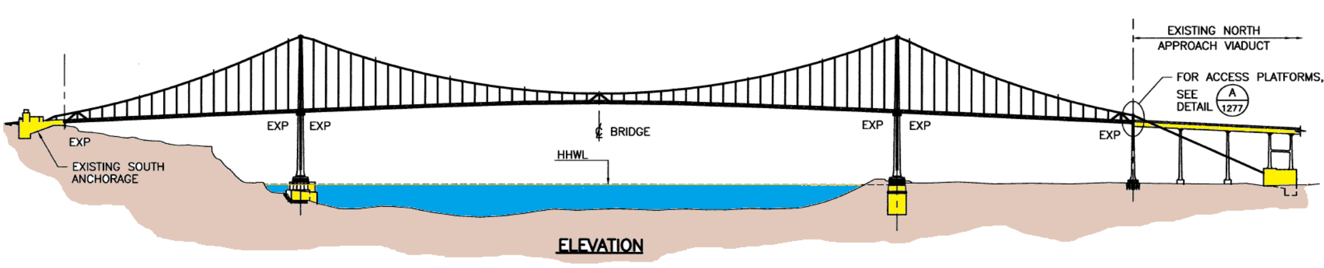

Figure 1. Lions Gate Bridge Suspended Spans Elevation.

There are four bearings that required replacement at each of the towers, providing vertical restraint and allowing rotations about a stainless-steel pin and a truss shoe. There are also two wind shoes at each tower, restraining transverse movement of the trusses. Figure 2 shows the bearing locations in greater detail.

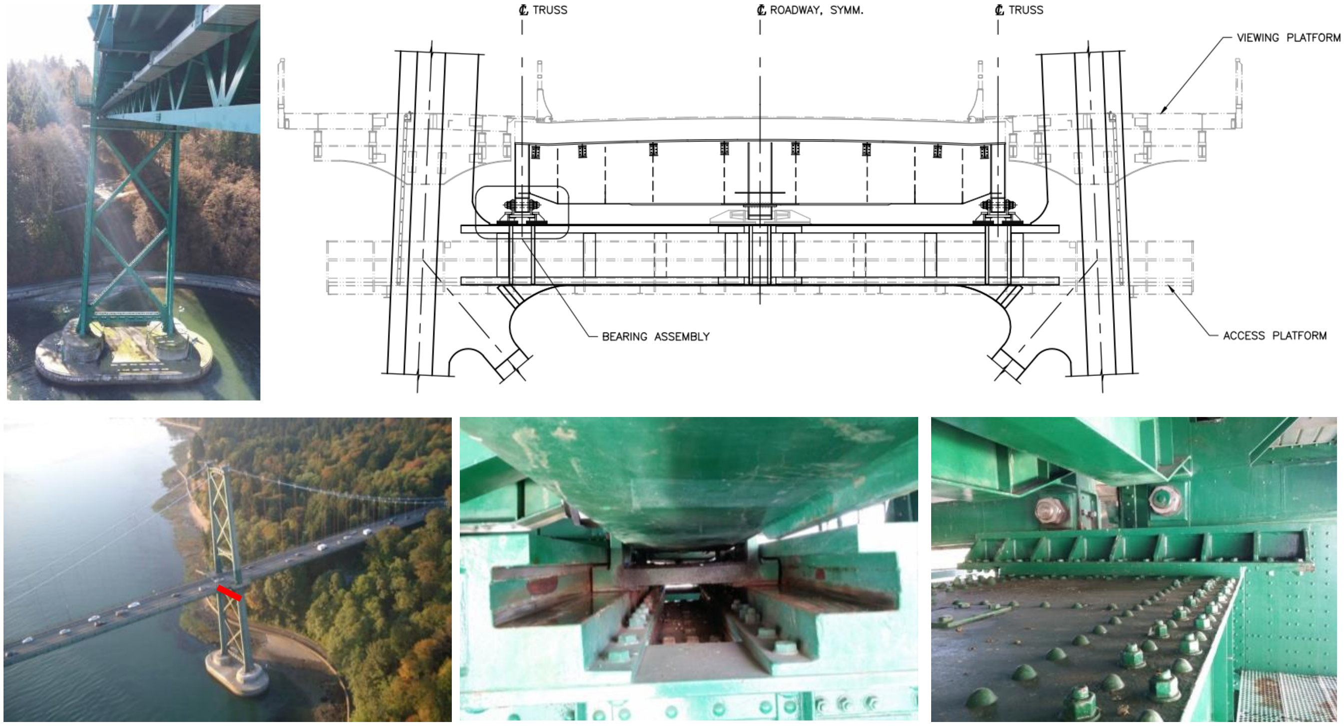

Figure 2. Clockwise from bottom left: Aerial view of south tower with tower strut highlighted in red; view of south tower from below deck; view of tower segment from drawings showing tower strut deck diaphragm, truss bearings; bearings within bearing guides supported on top of tower strut; previous deteriorated bearing shoe within bearing guides.

The width of the original bearing sliding surface below the pin was unusually small (bottom-right Figure 2), when compared to the eccentricity of the resisting friction force at the sliding surface level, in relation to the centre of the pin, about which rotation of the trusses occur. The sliding surface width was 300 mm at the tower bearings, compared to 550 mm at the abutment bearings, leaving the bearings at the main towers more susceptible to rotation about the pins than the abutment bearings. As part of the new bearing design the truss shoe guide surface was lengthened to 600 mm to reduce rotations. The length of the truss shoe was one of the improvements incorporated into the new bearing design. The other improvements are described below with reference to the new bearing design geometry shown in Figure 3.

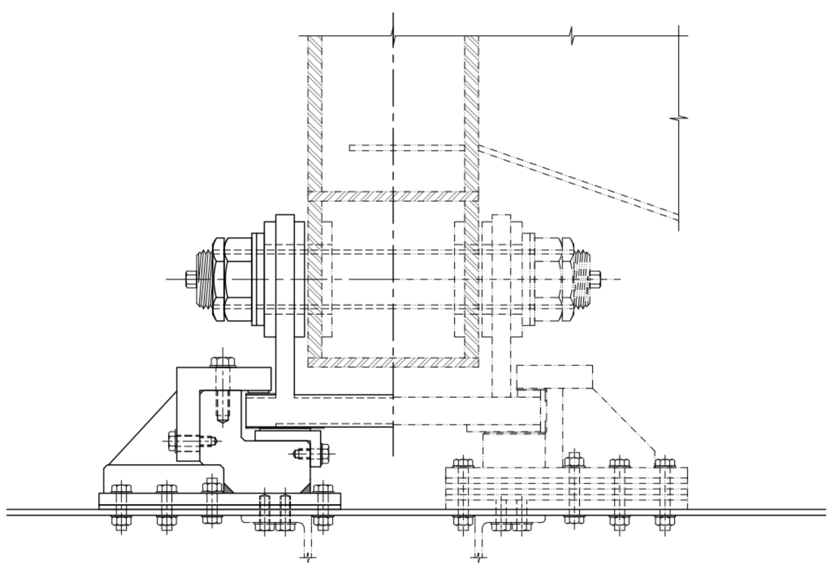

Figure 3. New bearing (left, solid lines) and previous bearing (right, dashed lines) geometry.

The PTFE sliding surface of the bearings was worn away, and the ASTM A572 grade 50 steel to which it is bonded was in direct contact with the stainless-steel sliding surface which showed signs of excessive wear. As the stainless-steel is the harder of the two materials, it caused wear in the grade 50 steel plate. This wear in turn, increased the gap between the truss shoe and the bearing guides, accentuating the tilting effect when the truss shoe experienced longitudinal sliding. Grit trapped between the two sliding surfaces appeared to cause work hardening of the steel as the grit dug into the mating surfaces and deformed the materials into the plastic deformation range, resulting in work hardened blobs of the stronger material. This can cause jamming as the blobs on the harder material embed themselves into the softer material. The jamming forces are then released as the bearing goes into uplift.

The previous bearing design required the truss shoe to be removed to replace the steel plates to which the PTFE was attached. This requires a lot of effort, for example, the side span truss shoes, which contain the rotating pin, cannot be removed without first removing the main span truss shoes. Hence the new bearing design incorporated a new maintenance scheme, where the wearing surfaces could be replaced with considerably less effort.

An additional novel feature of the new bearing design is the incorporation of a new wearing surface material, a modified Ultra-High-Molecular-Weight Polyethylene (UHMWPE) in place of the traditional PTFE. To the knowledge of the authors, this was the first time this material was used in this type of application in the region. UHMWPE was chosen as these materials are commonly used in spherical bearings and mechanical bearings, and have a long history of performing well in more demanding environments. Hence it was selected with a high degree of confidence that it would perform well, but a testing program was developed and carried out to provide reliable data demonstrating its performance. The testing program showed that the material was an excellent fit for the bearing, and would perform well in the field. As a further validation of the in-service performance of the wearing surface UHMWPE, and to monitor the performance of the new bearing design in general, an in-service monitoring program was also developed, this will be described in detail below.

MODELLING

Model Description

Several global finite element models of the bridge were created in Midas [3] to determine the loads for which the bearings should be designed. Static and dynamic analyses were conducted, that considered the nonlinear large displacements required in the analysis of a suspension bridge. A schematic of a global finite element model is shown in Figure 4.

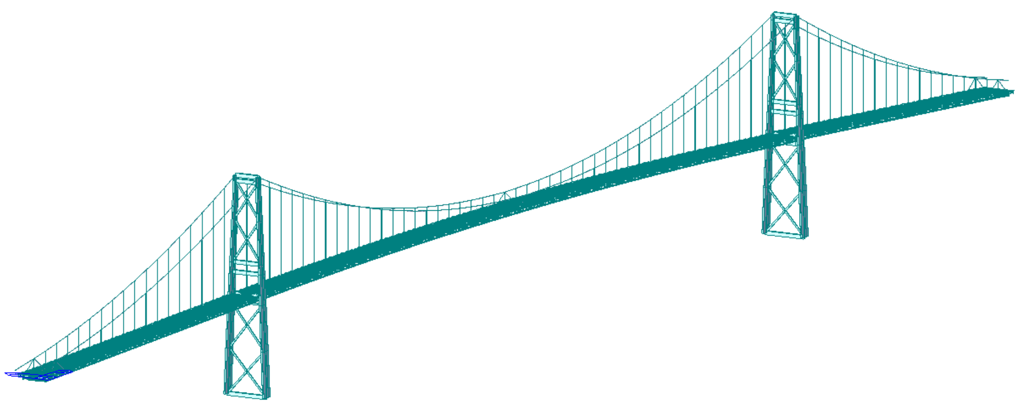

Figure 4. Finite element model of the bridge.

After the finite element model was created, and before the different load cases were applied and studied in earnest, the axial loads in the elements of the main towers were studied under the application of dead loads only, and these results were compared to those reported on the record drawings [4]. A second validation of the finite element model was conducted using the dynamic analysis and the natural modes of the bridge [5]. Together, these are considered evidence that the finite element model used in this work is accurate enough to be used in determining the demands on the bearings.

Analysis and Results

To design the bearings, the maximum required vertical forces in the downwards and upwards directions, and the maximum longitudinal displacements are required. These were obtained from the FE models, where different models were used for the static load cases and the time history load cases. The load cases to be analysed were generated in accordance with Section 3 of the Canadian Highway Bridge Design Code (S6-14) [6]. For example, the displacement results from those load cases to be analysed statically are shown in Figure 5 and those from the seismic analyses are shown in Figure 6.

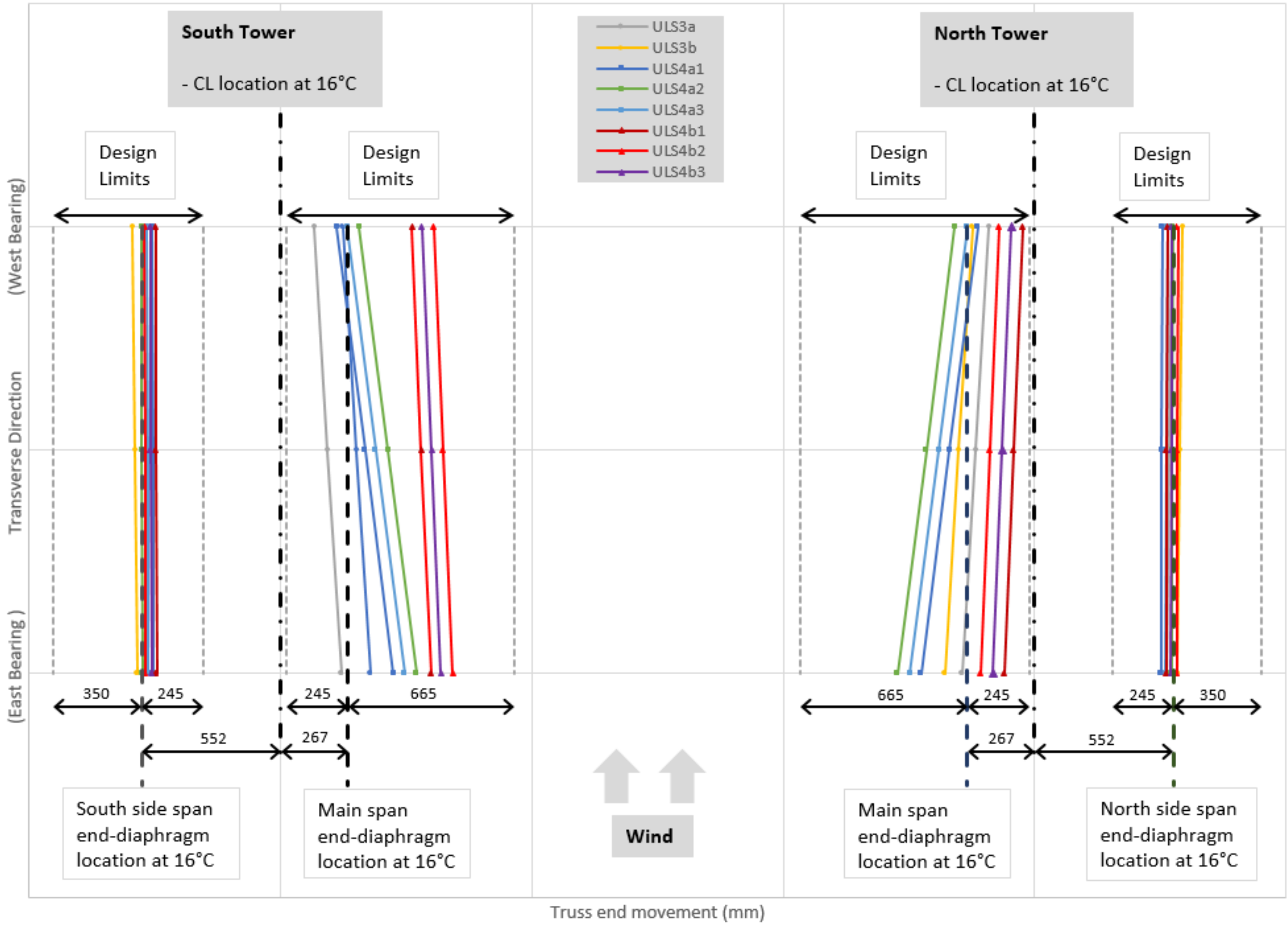

Figure 5. Longitudinal bearing displacement from static loads cases.

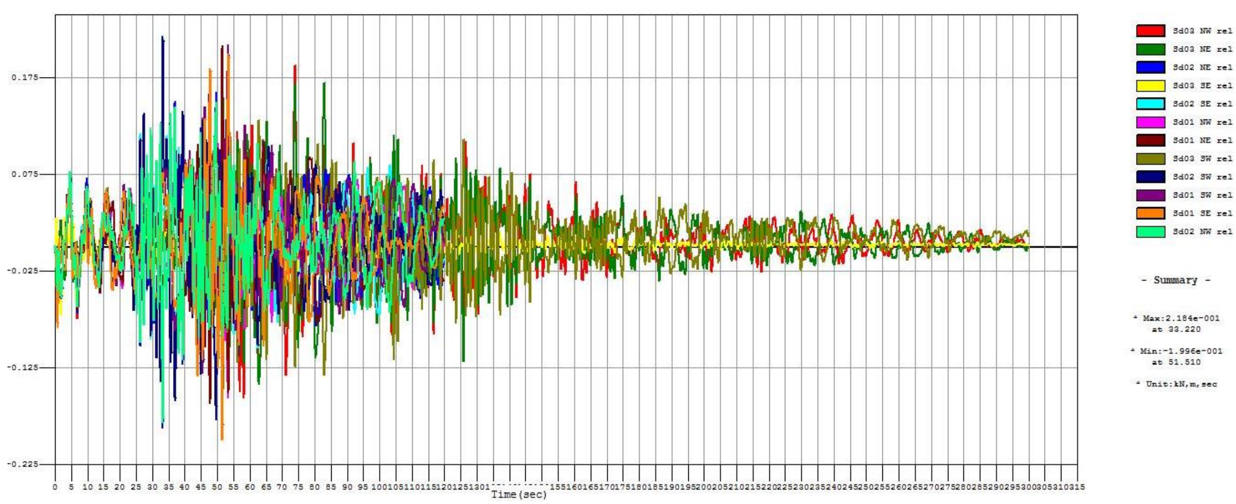

Figure 6. Opening (negative) and closing (positive) of the gaps, in metres, between the truss ends at the tower bearings for the subduction interface records.

As expected of a relatively light and flexible steel structure, the bridge is lightly damped. A value of 2% of critical damping is used in the analysis. The 1:2475-year return period Site Class C hazard values are obtained from the NRCan website. This is then modified using the modification factor given in S6-14. The records are matched using a slightly different period range for each source type. This is to account for the dominance of different source types within different period ranges of the UHS of Vancouver. For example, scaling a crustal record to match the UHS S_a value at 5s would produce a very warped crustal earthquake record. Table 1 gives a list of the earthquake records used for the analysis and some time-step information.

Table 1. Earthquake Records.

Record Name	**Earthquake**	**Length (s)**
Crustal		
C01	Kern	54
C02	Friuli	36
C03	Tabas	20
C04	Imperial Valley	63
C05	Irpinia	36
C06	Irpinia Pulse	34
C07	Loma Prieta	39
Subduction intraplate		
Sc01	Geiyo	119
Sc02	Miyagi Oki	189
Sc03	Nisqually	116
Subduction interface		
Sd01	Hokkaido	192
Sd02	El Maule	120
Sd03	Tohoku	300

The maximum range of movement was found to be closing of a truss end into the northwest bearing by 313 mm, and an opening out of the truss end at the southeast bearing by 294 mm. This gives a range of 606 mm if it were at a single joint. Note that the maximum values are not concurrent, or are they located at the same bearing. Hence reporting the range of movement in this manner is conservative, and it remains lower than the thermal requirements given on the record drawings of 790 mm. All the bearings are designed for the maximum uplift and downwards forces experienced by any one of the bearings. Hence, all bearings will be designed to accommodate the currently designed range of motion, as it exceeds anything found in the analyses conducted here. The bearings will be designed for 1371 kN downwards vertical force, and 812 kN upwards force.

NOVEL SLIDING SURFACE MATERIAL

The sliding surface material included in the bearings installed in 2001 was PTFE. The PTFE slid on stainless-steel, but at the time of the design of the current bearing replacement, the PTFE had completely worn away in many locations, resulting in the stainless-steel sliding directly on the mild steel of the bearing assembly. During the new bearing design, three new materials were considered in place of the PTFE. The new materials were UHMWPE variants, similar to materials used in mechanical bearings or in other demanding environments. As these materials were not used in such bearing applications in the region, a testing program was devised to demonstrate their suitability. The bearing materials were tested systematically, to failure, as can be seen in the example test shown in Figure 7. As a result of the testing program, a solid-lubricant-filled UHMWPE material was selected and installed in the new bearing assemblies.

Figure 7. Testing a UHMWPE specimen to buckling failure.

MONITORING AND INSTRUMENTATION

The performance history of the original bearing design and the inclusion of the novel wearing surface material prompted the inclusion of Structural Health Monitoring (SHM) instrumentation into the bearing design. When it was decided to include instrumentation, it was thought prudent to include Seismic Instrumentation at the same time.

The SHM instrumentation includes 33 channels of data acquisition system: eight displacement sensors, five acceleration sensors, four tilt meters, and two weather stations (temperature, wind speed and direction). The sensors are connected to the two data recorders, which are located at each end of the bridge. The two data recorders are connected via fibre optic cable, and the entire SHM system streams real-time data to British Columbia Smart Infrastructure Monitoring System (BCSIMS) through the BC government fiber optic network [7]. The final instrumentation layout is given in Figure 8.

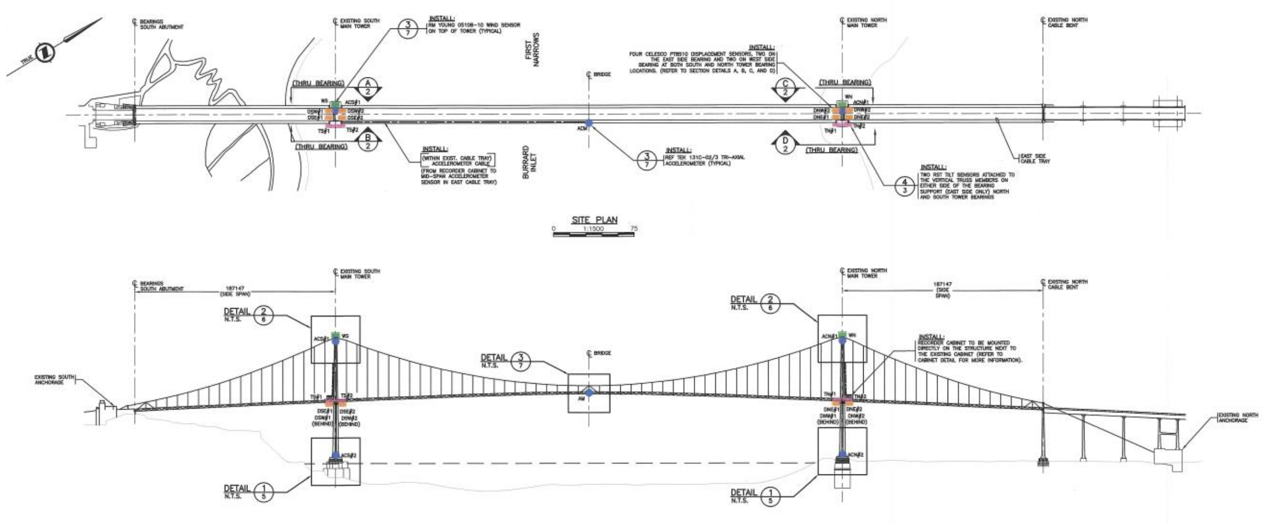

Figure 8. Instrumentation layout.

Displacement sensors are installed between the truss shoe and the bearing guide to measure the relative displacement between them. The measured displacement is analysed in real-time and stored in the BCSIMS data centre. The analysis results are then compared to the predefined threshold values to make sure that the displacement readings from each bearing are within expected range of bridge behaviour that takes into account the seasonal and daily temperature variations and daily traffic load acting on the bridge deck.

Four tilt meters are installed on the truss members to measure the inclination of the truss vertically and horizontally in real-time (Figure 10). Tilt readings together with the displacement sensor readings are used to determine the exact relative position of the truss shoe with respect to the bearing guide. The relative position of the truss shoe is then used to determine if the daily and seasonal bearing movement is as expected, or whether it may be stuck somehow. This automated process triggers a visual inspection if any of the bearings are stuck or jammed in place.

All analysis results are then used to produce scheduled SHM reports from the bridge. The report includes the samples of the recorded raw data, analysis results and any warnings, suggestions or recommendations regarding visual inspection. These reports are generated monthly and sent to a predefined list of recipients of the Ministry of Transportation and Infrastructure.

Two acceleration sensors are installed at each tower of the bridge: one at the foundation level and other at the top of the tower. The objectives of these instruments are (1) to measure the input motion at each tower base, (2) to estimate the total displacement at the top of each tower, and (3) to estimate the total drift experienced by each tower during strong shaking. The SHM system uses a smart voting-based algorithm to detect and respond to earthquake shaking. A seismic SHM report is produced following a significant earthquake, and it is then immediately sent out to the predefined list of recipients.

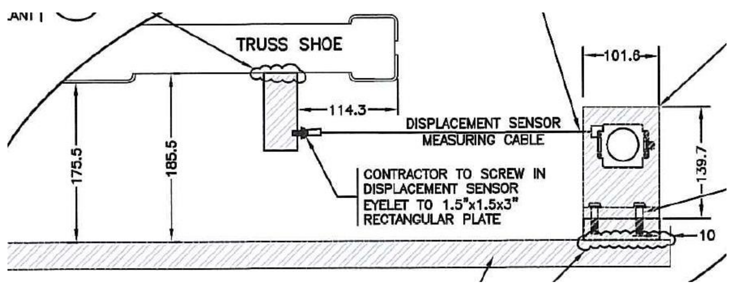

Figure 9. Location of the displacement sensor on bearings.

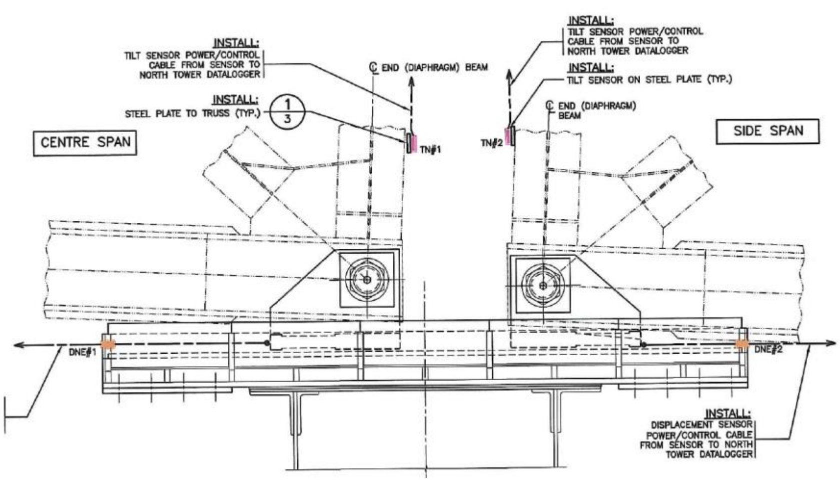

Figure 10. Location of the displacement sensor on bearings.

CONCLUSIONS

The Lions Gate Bridge is a landmark structure in Vancouver, and at over 80 years old, both the suspension spans and approach viaduct spans, have required retrofit and rehabilitation work in the past. The entire suspension span deck structure was replaced during weekend closures in 2001, which included vertical and lateral restraint bearings at the main towers, south abutment and north pier between the suspended span and viaduct. The vertical main tower bearings installed in 2001 failed and have been replaced as part of the work described herein. The combined loading, displacement, frequency of movement and maintenance requirements of the bearings are particularly demanding, and require careful consideration. The forces on the bearings are predominantly downwards, but frequently upwards; the design longitudinal movement range is over 600mm; the bearings are almost constantly moving as temperature, environmental loads and traffic loads all contribute to longitudinal movement; the new bearing design allowed for maintenance without requiring the entire bearing assembly to be disassembled, a difficult undertaking which was required for the previous design. The determination of the bearing design parameters required static and time-history analyses using finite element methods. To accommodate the movement requirements a novel UHMWPE material was used, which required an associated testing program to demonstrate its suitability to the conditions. To check that the installed bearings functioned as per the design and that the design parameters had been determined correctly, a Structural Health Monitoring (SHM) system was designed and installed at the same time as the new bearings, complete with the capability to stream real-time data to the British Columbia Smart Infrastructure Monitoring System (BCSIMS) through the BC government fibre optic network. When it was decided to include instrumentation, it was thought prudent to include Seismic Instrumentation at the same time. The SHM instrumentation includes 33 channels of data acquisition system: eight displacement sensors, five acceleration sensors, four tilt meters, and two weather stations (temperature, wind speed and direction).

ACKNOWLEDGMENTS

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