Model Updating of the Ironworkers Memorial Second Narrows Bridge, Vancouver, Canada

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The Ironworkers Memorial Second Narrows Crossing is a critical transportation link in the Lower Mainland Region of British Columbia, Canada, which is a zone of high seismic risk. The IMSNC is being instrumented as part of a real time seismic and health monitoring system, which will also include many other bridges around the region. As part of the system, a finite element model has been developed and updated using previously obtained ambient vibration measurements. This paper focuses on updating of one approach truss section of the bridge. The model was updated in several steps using both manual and automated techniques. Updating included stiffness of a set of seismic isolators that were added to the bridge in a retrofit in the mid 1990's. The complete updated set of models will be used in fatigue and damage studies as a part of the monitoring system.

1 INTRODUCTION

The Ironworkers Memorial Second Narrows Crossing (IMSNC) is the second bridge constructed at the Second Narrows of Burrard Inlet in Vancouver, British Columbia, Canada. It is an essential transportation corridor along the Trans-Canada highway (Route 1), connecting the City of Vancouver to the District of North Vancouver, the City of North Vancouver, and West Vancouver.

Vancouver is located in a zone of high seismic hazard in Western Canada. New evidence about potential earthquake sources, magnitudes and seismic activity in the area indicated the bridge would not withstand the design earthquake as per current code with the seismic design of the 1950's. The bridge was then retrofitted in 1994 by strengthening some elements and changing some of the original expansion and pin-bearings to isolation bearings.

The Ministry of Transportation and Infrastructure (MTI) and the University of British Columbia (UBC) have initiated a structural health monitoring program of bridges in the province of British Columbia. The purpose of the program is to detect damage of the structures using field data and state-of-the-art damage detection algorithms. The IMSNC is one of those bridges that will be instrumented. As part of the system, a finite element model has been developed and updated using previously obtained ambient vibration measurements [Ventura et al., 2009].

This paper presents the results of an updating study as performed on a portion of model of the IMSNC. The updating was done in two phases; the first to obtain a working stiffness value for a set of seismic isolation bearings installed in several locations on the bridge and the second to update several modes of a typical approach truss. The updated model will be used in fatigue and damage studies as a part of the monitoring system.

2 DESCRIPTION OF THE IMSNC

The Ironworkers Memorial Second Narrows Crossing is a 1292m-long composite structure. It carries six lanes of traffic (three lanes for each direction) and a 0.6m-diameter gas pipeline. The general configuration of the bridge and bent designation is illustrated in Figure 1. This paper focuses on a typical approach truss (between Section 10 and 11) only. For detailed information on the entire bridge see [Ventura et al. 2009].

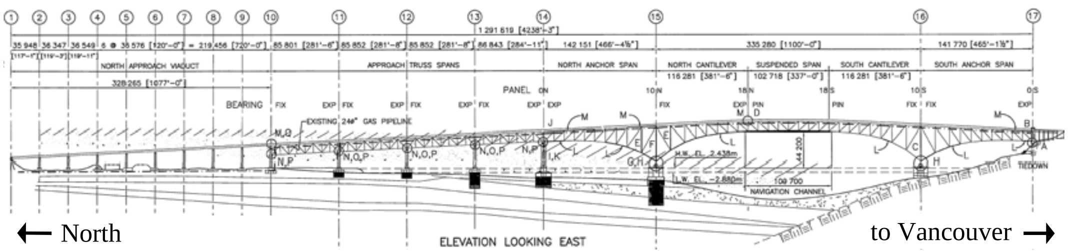

Figure 1: General configuration and bent designation of the IMSNC.

There are four 86.0m-long steel approach truss spans starting on the North shore of the crossing and extending out into the inlet. Each span has two 13.0m-depth custom steel warren trusses separated 14.6m apart. Both trusses are connected by horizontal and vertical bracing. The 0.2m-thick RC deck slab is supported on thirteen 0.8m-depth steel I-girders in the longitudinal direction and on a 1.7m-depth x 22.0m-long steel I-floor beam located transversally every 10.5m along the truss. The longitudinal girders are also connected transversally every 3.5m by a 0.5m-depth steel I-girders. The warren trusses are supported on isolation bearings protected with bumpers. The deck has transverse expansion joints at the ends of each span, so there is no structural continuity among them. The transition between two approaches and between the southernmost approach and the main cantilever section of the bridge is shown in Figure 2.

a) Deck floor and steel warren trusses

b) Bent 14: south end of the approach truss spans

Figure 2: Approach truss spans.

3 REAL-TIME SEISMIC MONITORING SYSTEM

A real-time monitoring system (RTMS) is currently being installed on the IMSNC. The monitoring system will part of a province wide network, with its central hub located at the University of British Columbia (UBC) in Vancouver, Canada. The monitoring system will provide real-time information regarding structural performance and safety, primarily for seismic, but also applicable for a variety of load types. The monitoring system will be implemented in two phases: first to install the on-site hardware and second to implement a customized software and data processing system unique to the MTI/UBC network.

The general purpose of the system is to monitor the structural health of the bridge for seismic, impact and deterioration effects. This considers two loading levels: severe infrequent events, such as seismic and impact/collision; and frequent long-term effects, such as wind, traffic, etc. The system instrumentation will consist of:

- Vibration measurements utilizing uni- and tri- axial accelerometers
- Strong motion measurements off the structure, including free-field and down-hole accelerometers
- Strain measurements on the deck floor beams and major truss elements
- Temperature measurements at several locations, both the North and South ends
- Wind speed measurements at midspan

The data will be collected at a central data recorder, in which a certain amount of on-site data processing will occur. Then processed and raw data will be sent to UBC for further processing and storage. The monitoring system has approximately 100 channels; however due to the configuration of isolation bearings and expansion joints, the bridge is essentially split into 10 smaller independent structures. This means that in reality there is an average of about 10 channels per structure.

4 SUMMARY OF AVT RESULTS

A comprehensive ambient vibration test program of the IMSNC has been planned in several phases, the first of which was carried out in January 2009. This phase included testing of the entire bridge along the deck. For full details of the testing including test locations please refer to [Ventura et al., 2009]. Future phases include detailed testing of the trusses and piers.

Identification of modal vibration properties of the IMSNC was performed using ARTeMIS Extractor [SVS, 2009]. Several system identification techniques are available in the software including Stochastic Subspace Identification (SSI) and Frequency Domain Decomposition (FDD). Typically data was processed using the automated identification feature in the software, with the SSI-CVA algorithm. The analysis as described here focused only on the approach trusses, and the data was processed in the 0-5Hz bandwidth.

Two different tests were performed on the approach trusses. First the *simplified test*, measuring three orthogonal directions at two locations at midspan of the approach (one on either side of the bridge); the simplified test was repeated on each of the four approaches. Second the *detailed test*, measuring three orthogonal directions at 36 locations along the approach, 18 on either side. The detailed test was only performed on one of the approaches.

Four modes below 5Hz were identified in each of the four simplified tests, listed in Table 1. The modes include a horizontal mode in each orthogonal direction (modes 1 and 2), which are considered as rigid body modes. This rigid body behavior is caused by the isolation bearings at the four corners, which are flexible relative to the truss. From the detailed test, only the last two modes were clearly identified. This could be explained by the fact that the simplified tests were recorded for twice the duration of the detailed test; the reduced dataset length does not allow for the proper identification of the lowest frequency modes. Consequently updating using the first two modes will be based on frequency only; the third and fourth modes will compare frequency and mode shapes.

Table 1: Ambient vibration results.

Mode	Freq. [Hz]	Descr.
1	1.34	Transverse rigid body
2	1.56	Longitudinal, rigid body
3	2.38	1st Vertical
4	3.06	1st Torsional

5 FINITE ELEMENT MODEL

A finite element model of the IMSNC has been developed, partly from a previous model that was used in the 1994 retrofit of the bridge; the original model was created in SFRAME [SOFTEK, 2009] format. Subsequently the bridge was remodeled into SAP2000 [CSI, 2009], and then input to FEMTools [DDS, 2008] for the updating. SAP2000 is an industry standard finite element analysis software, which will be used for structural analysis of the bridge. FEMTools is a multi-function tool that has capabilities for validation and updating of FE models.

The FE model consists of a series of frame elements with added masses; in general the elements are typical W sections for braces, beams and stringers, and custom rectangular elements with equivalent properties to represent the built-up sections found in the truss. The seismic isolation bearings are modeled as link (spring) elements with axial stiffness only. The links are then placed in each of the orthogonal horizontal directions at each of the four supports. A single approach truss section as described in this paper is shown in Figure 3a. A typical isolator of the type used at IMSNC is shown in Figure 3b.

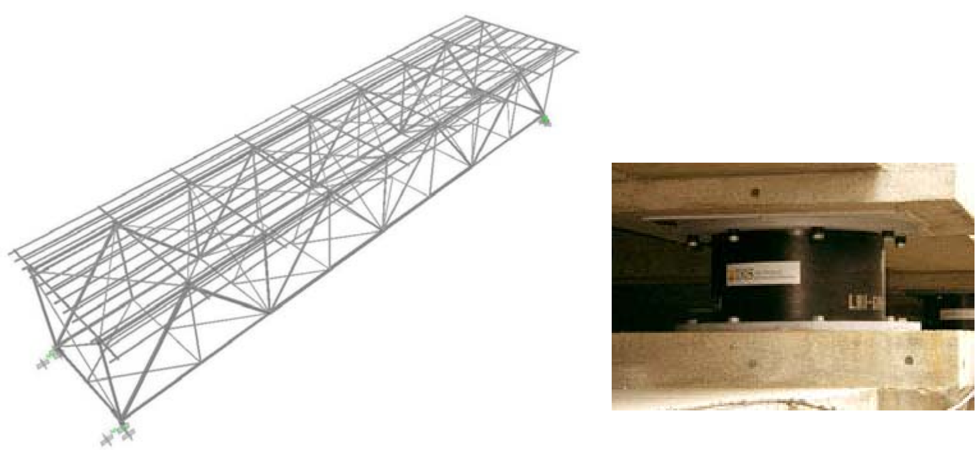

Figure 3: a) FE model of typical approach truss span b) typical seismic isolation bearing

To establish the translational stiffness (K) of the bearings, it was first assumed that the second mode from the AVT results could be treated as a SDOF system. This is based on the idea that the truss is very stiff longitudinally compared to the bearings, and so the stiffness (in mode 2) comes only from the bearings and the truss acts as the mass. The bearing stiffness is then tuned as to match the frequency of the FE Model second mode to the AVT result (1.56Hz). The modes of the original pinned model are given shown in Table 2; the transverse mode is shown at 1.78Hz with no longitudinal mode observed below 5Hz. To obtain the starting value of K for the bearings, first the translational restraint in the transverse direction was removed. The value of K was then manually tuned until a reasonable match of frequency was obtained; this resulted in the preliminary value of 40MN/m, with a second mode frequency of 1.64Hz. Then the longitudinal-direction restraints were removed, and using the same K value for the links in that direction the rest of the modes were computed (shown in Table 2).

Table 2: SAP2000 model results

Mode	**AVT**	**Descr.**	**SAP2000 (Pinned model)**	**SAP2000 (Iso. model)**	**Difference (Iso. vs AVT)**
	Freq. [Hz]		Freq. [Hz]	Freq. [Hz]	[%]
1	1.34	Trans, rb	1.78	1.23	-8.94
2	1.56	Long, rb	N/A	1.64	4.88
3	2.38	Vert	2.99	2.57	7.39
4	3.06	Tors	3.72	3.40	10.00

*trans only, no rigid body

6 FINITE ELEMENT MODEL UPDATING

The model updating presented in this paper has two stages. The first stage is to determine a reasonable working stiffness for the seismic isolation bearings; the second is to do a general overall updating of the truss. The preliminary updating of the bearing stiffness was presented in the last section, with results shown in Table 2.

The software FEMTools (FT) was used for both automated and manual updating of the truss. The initial SAP2000 model described in the last section was imported into FEMTools using a code translator developed at the University of British Columbia. The initial FT model modes are shown in Table 3. There are very small differences between FT and SAP, but as shown in the table the FT initial frequencies are identical to the SAP results. The first updating step is to automatically change the stiffness of the longitudinal bearings to obtain a match in the second frequency; the updated stiffness will then be used for the transverse direction bearings as well. The results are shown in the Table 3 as Update 1 (UD1). One consequence of the second mode frequency match is that the first mode also decreases in frequency (expected since K is updated in both horizontal directions). The updated stiffness value, which will be used for all the bearings on the bridge, is 35.2MN/m (a parameter change of -12%).

Table 3: Updating results, bearing stiffness.

Mode	**AVT**	**FT (initial)**	**Difference**	**FT (UD1)**	**Difference**
	Freq. [Hz]	Freq. [Hz]	[%]	Freq. [Hz]	[%]
1	1.34	1.23	-8.24	1.19	-11.08
2	1.56	1.64	5.56	1.55	-0.16
3	2.38	2.57	10.22	2.57	10.02
4	3.06	3.38	7.79	3.36	7.17

The second updating step addresses the difference in first mode frequency (-11%). Assuming that the bearings have the same stiffness in all directions and that the mass of the truss contributes the same in both horizontal directions, then the difference in frequency between modes 1 and 2 must be a result of contributions of the truss transverse bending stiffness. The truss model elements were separated into sets for the updating: top and bottom chords, east and west sides; top and bottom diagonals, north and south groups. A normalized sensitivity analysis was performed on element sets using FEMTools. The analysis was done comparing the first mode frequencies as the response for matching, and using modulus of elasticity, E, and moment of inertias, Iy and Iz as potential parameters for updating. The resulting sensitivity matrix is shown in Figure 4. It is given here as a typical example and further sensitivity matrices will not be shown.

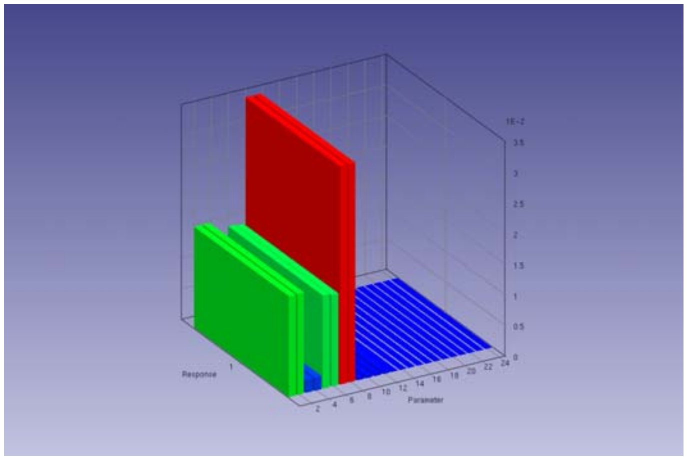

Figure 4: Sensitivity matrix, lateral elements

From the analysis it was found that the transverse mode is most sensitive to changes in the top diagonal properties. A trial updating was performed using modulus of elasticity, E, of top diagonals as the parameter, and its value was allowed to change without restriction. A very close match could be obtained (FEA to 1.30Hz) with a large parameter change (+630%). The implication is that the concrete deck slab, which was previously ignored in the model except as contributing only as mass, has a potentially significant effect on lateral stiffness. Therefore a series of additional lateral braces were added at the deck level, given a unit area, negligible mass and an initial E value of 2 x10^5 MPa. The model was then manually updated by increasing E; it was found that there was a maximum obtainable frequency of 1.315 Hz (meaning further increases of E had no effect on frequency). This limit occurred at an E value of 2.5 x 10^5 MPa. The updated modes from the additional braces are shown in Table 4, as Update 2 (UD2). A side effect of adding the additional braces is that there is an increase in the frequencies of modes 3 and 4 (as expected).

Table 4: Updating results, lateral (2) and vertical (3)

Mode	**AVT**	**FT (UD2)**	**Difference**	**FT (UD3)**	**Difference**
	Freq [Hz]	Freq [Hz]	[%]	Freq [Hz]	[%]
1	1.34	1.32	-2.07	1.34	-0.03
2	1.56	1.55	-0.15	1.56	0.09
3	2.38	2.60	11.19	2.39	0.42
4	3.06	3.64	15.81	3.36	8.93

The last stage is to update the 2nd and 3rd modes. This can be done using the results from the detailed ambient vibration test, which includes modes shapes and MAC values (modal assurance criterion, MAC, is a commonly used indicator to compare mode shapes, given in percent). Table 5 shows a comparison of the 3rd and 4th modes. From the results of the previous updating step (UD2), it can be seen that the MAC values are already reasonably high, being both over 90%. Both of the frequency values are higher, implying that the truss is vertically too stiff. Therefore it is meaningful to examine the behavior of the vertical chords/diagonals of the model.

A sensitivity analysis was again performed, and from the results it was seen that the moment of inertia properties were the least sensitive; they were removed from the updating. Since the initial MAC values were already high, the updating response chosen to match was the 3rd mode frequency, and the updating parameter was the cross sectional area of the vertical diagonal element set. The area was reduced by 25%, then automatically refined for a total area reduction of 53%. The results are shown in Table 5 referred to as Updating 3 (UD3). The first mode frequency matched nearly perfectly; the second mode error was reduced by half. In addition, for both modes the MAC value increased.

Table 5: Updating results, comparing 3rd and 4th modes with MAC values.

Mode	**AVT**	**FT (UD2)**	**Difference**	**MAC**
	Freq [Hz]	Freq [Hz]	[%]	[%]
3	2.38	2.60	9.14	96.1
4	3.06	3.64	18.96	90.7
Mode	**AVT**	**FT (UD3)**	**Difference**	**MAC**
3	2.38	2.39	0.63	96.7
4	3.06	3.35	9.50	93.2

Even though Updating 3 focussed on the 3rd mode (vertical) there is a change to the 4th mode (torsion) as expected. While there is sizeable improvement there remains some error. A further updating was explored to reduce this error; the primary focus was on the vertical braces located at 5 locations along the truss (these brace against transverse deformation of the truss). Despite several variations of the updating step, no significant improvement in torsional frequency match was made.

7 SUMMARY AND CONCLUSIONS

This paper presented the results of a model updating study on a typical approach truss of the Ironworkers Memorial Second Narrows Crossing (bridge), in Vancouver, Canada. The updating study was successful at achieving two primary objectives: to obtain a working stiffness value for the bridge seismic isolator bearings and to obtain a well-correlated dynamic model.

Results of a series of ambient vibration tests were used in the updating; four modes of vibration were obtained in those tests. These included two horizontal rigid-body type modes which were indicative of the isolator bearing stiffness; and two structural modes of the truss including vertical and torsional. The rigid body modes were used to find a working stiffness value for the bearings, identified as 35.2MN/m. The frequency and shapes of all four modes was used to modify the model, and the results of the updating has errors of less than 1% on each of the first three modes; and less than 10% for the fourth mode. The MAC values for the 3rd and 4th mode were both greater than 93%.

The results of the final step of the updating feature a large parameter change; the cross-sectional area of the vertical truss diagonals was reduced by 53%. This is not a realistic physical parameter change; however for a constructed system such as IMSNC there is significant uncertainty in properties of built-up, riveted members that have been in service for nearly 60 years. It is more reasonable to assume that changes to modulus and section properties would be distributed throughout the truss. Further study will be done on the model using:

- The working stiffness value for the isolator bearings
- Data from future ambient vibration tests, including more detail of the truss
- Data from the monitoring system

ACKNOWLEDGMENTS

The authors would like to acknowledge Ms. Sharlie Huffman, from the Ministry of Transporation and Infrastructure of British Columbia. They would like to acknowledge Mr. Juan-Carlos

Carvajal and the students at the University of British Columbia who performed the testing on the bridge. They would also like to acknowledge Mr. Devin Sauer of the University of British Columbia for his work on updating the SAP2000 translator for Version 12.

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