ANALYTICAL MODELLING FOR THE SEISMIC ASSESSMENT OF THE PEACE TOWER, PARLIAMENT OF CANADA

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Abstract

At 92m tall, the Peace Tower is a dominant feature of Canada's heritage-designated Parliament buildings and a widely recognized symbol of Canada. This paper presents the approach used to develop and verify an analytical model of the tower suitable for conducting a seismic assessment. Due to inherent complexities within the Peace Tower's geometry, an atypical modelling approach was required. Analytical building models typically approximate structural components with finite line and finite area elements located at component centerlines. This approach is less applicable when modelling historic structures which, like the Peace Tower, have massive structural components with non-aligned centroids. Models constructed using solid elements (e.g. 8-node objects) address some of the limitations of finite line/area element models; however, analysis of these models can be onerous to compute. A computationally simpler approach is to use custom finite line and finite area elements, located at component centrelines and connected to other elements with rigid links where offsets in component centroids occur. For the Peace Tower seismic assessment, both a finite line/area element model with rigid links and a solid element model were constructed to perform separate analyses. The solid element model was used to verify the acceptability of the simplifications inherent to the finite line/area element model which, unlike the solid element model, could then be incorporated into a larger global model of the building complex that the Peace Tower adjoins. The stiffness of the finite line/area element analytical model was then calibrated to match a range of dynamic characteristics observed during ambient vibration testing of the Peace Tower, as well as its recorded response to the 2010 Val-des-Bois earthquake. It is concluded that the simplified finite line/area element model, with rigid links, which accommodate offsets in structure component centroids, satisfactorily replicated the dynamic response of the more complex solid finite element model. Calibration of the model provided a dynamic response to the time-history acceleration record of the Val-des-Bois earthquake that was a close match to the actual recorded response of the Peace Tower to the earthquake.

Keywords: Peace Tower; Analytical modelling; Seismic assessment; Historic masonry.

1. Introduction

The Peace Tower is a dominant feature of Canada's heritage-designated Parliament buildings and a widely recognized symbol of Canada [1]. Figure 1 shows the Peace Tower and adjoining Centre Block. The Peace Tower and Centre Block were constructed between 1916 and 1924 on the site of an earlier version of the Centre Block that was destroyed by fire [2].

Figure 1: Centre Block of the Canadian Parliament, Ottawa

The Peace Tower and Centre Block are currently undergoing a major rehabilitation. Part of the rehabilitation scope includes a seismic upgrade. As a precursor to the design of the seismic upgrade, an analytical model of the Peace Tower was developed using CSI's SAP 2000 software. The primary purpose of the model was to aid the determination of seismic demand on key structural elements.

Due to the inherent complexities within the Peace Tower's geometry, an atypical modelling approach was required. Typical analytical building models approximate structural components with finite line and finite area elements located at component centrelines. This approach becomes complicated when modelling historic structures that have massive structural components with non-aligned centroids. Models constructed using solid elements (e.g. 8-node objects) overcome some of the limitations of finite line/area element models; however, analysis of these models can be computationally onerous. A computationally simpler alternative is to use custom finite line and finite area elements, located at component centrelines, connected to one another by rigid link elements where offsets in component centroids occur.

For the Peace Tower seismic assessment, both a finite line/area element model with rigid links and a solid element model were constructed to perform separate analyses. The solid element model was used to verify the acceptability of the simplifications inherent to the finite area/line element model which, unlike the solid element model, could then be incorporated into a larger global model that included the adjoining Centre Block. The development of the two analytical models and their verification is reviewed in Section 2.0.

Subsequent to the verification of the finite area/line element model, the stiffness of the Peace Tower model was calibrated to closely match the dynamic characteristics observed during both an ambient vibration test and the recorded response of the Peace Tower to the 2010 Val-des-Bois earthquake. The calibration of the model stiffness and review of its dynamic response is presented in Section 3.0.

2. Analytical model

2.1 Structural system

The Peace Tower's primary structural elements are its corner piers and the spandrels that connect them intermittently over its height. Figure 2 shows an elevation of the Peace Tower with the primary structural elements identified. A mixture of structural systems was used in its construction. The piers of the Peace Tower were constructed with unreinforced concrete and an exterior wythe of sandstone masonry. The spandrels vary in composition but are typically composed of unreinforced concrete with stone wythes, reinforced concrete, structural steel beams embedded in concrete, or a combination of these materials. The Peace Tower resists wind and seismic loads via frame action of its corner piers and spandrels.

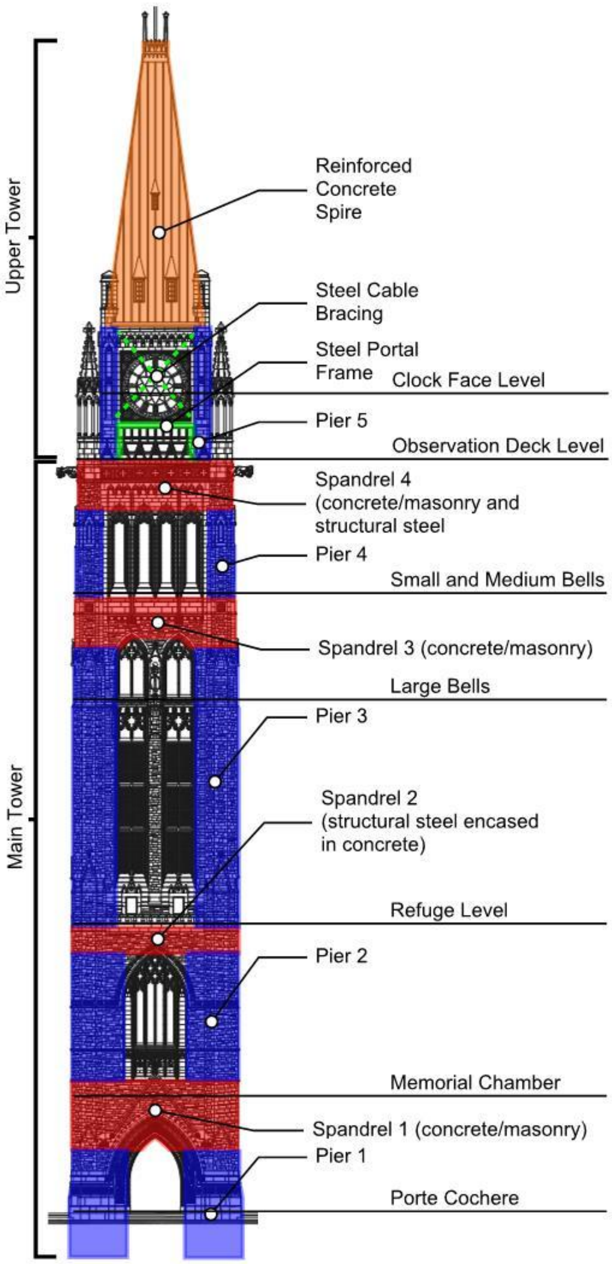

Figure 2: Primary structural elements of the Peace Tower

2.2 Pier modelling

The Peace Tower's corner piers vary in plan at different elevations, decreasing in area over the height of the tower. Figure 3 illustrates the corner pier shapes at various levels. The pier centroid shifts through the height of the tower with the changing shape of the piers, as illustrated by the non-concentric circles in the plan detail. As noted in the introduction, in the finite line/area model the corner piers were modelled using custom frame elements. An example of a custom section is provided in Figure 4. To accurately recreate the shifting centroid of the corner piers in the finite line/area analytical model, the custom frame elements representing each unique section of the corner piers were located at the true centroid of each section. Consequently, the frame elements were not co-linear throughout the height of the tower, i.e. they were vertically discontinuous at the interface of each pier section. To resolve this analytical discontinuity and provide a valid load path, the ends of the corner pier frame elements were connected using horizontal rigid link elements (see Figure 5).

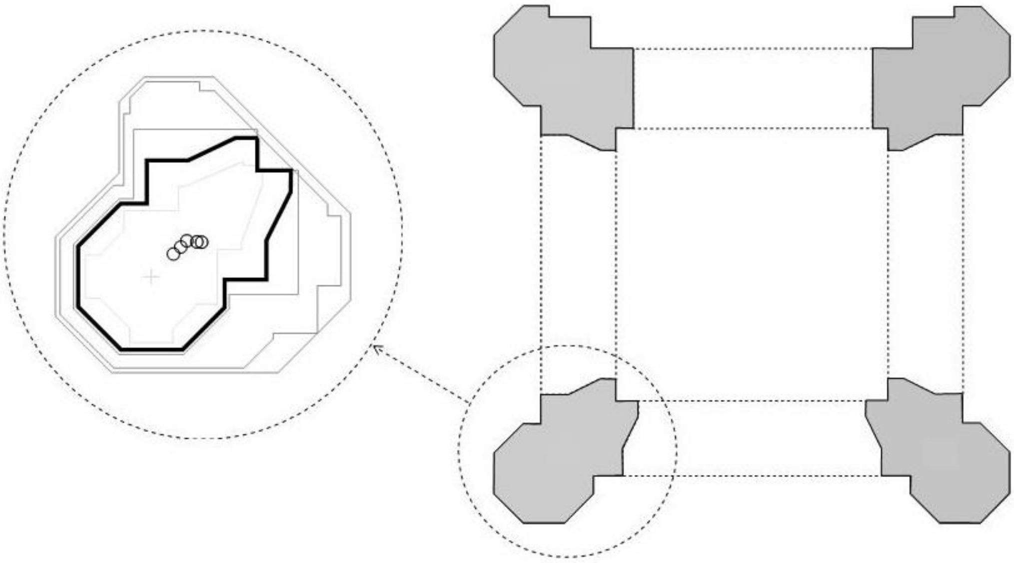

Figure 3: Peace Tower plan

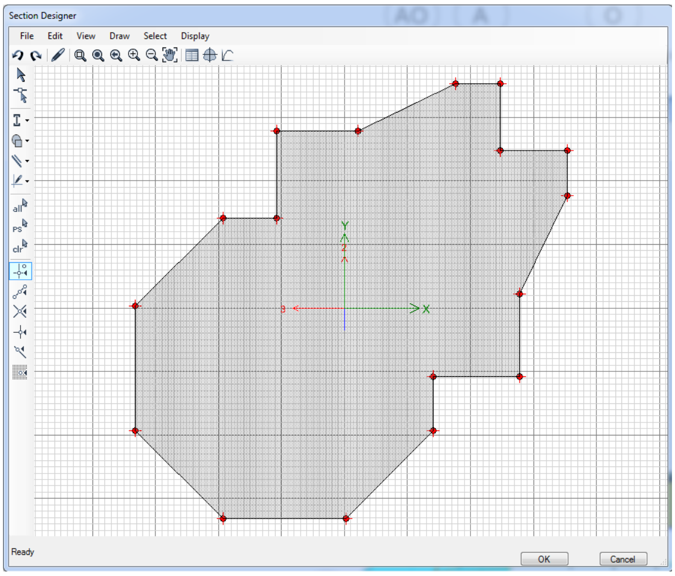

Figure 4: Example of custom frame section developed using the CSi's Section Designer tool

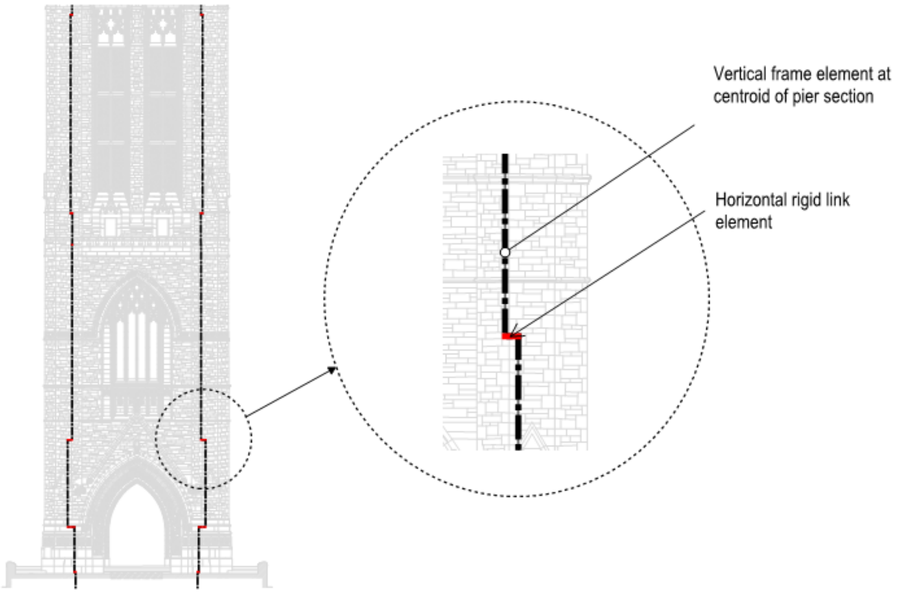

Figure 5: Vertically discontinuous frame elements connected with rigid frame elements

2.3 Spandrel modelling

In both the finite line/area element model and the solid finite element model, the Peace Tower's spandrels were modelled using two-dimensional shell elements. An overlap of the analytical spandrel elements with the corner piers was avoided in the line/area element model by limiting their extents to the inside faces of the corner piers, thereby preventing an overestimation of the corner piers' mass and stiffness. This is illustrated in Figure 6, which shows a plan section through the finite line/area element model. Rigid links were used to connect the spandrel elements to the corner pier frame elements. The plan centrelines of the spandrel shell elements were located to match the true centrelines of the Peace Tower's spandrels. The centrelines of these elements vary throughout the height of the tower due to setbacks in the exterior walls and changes in wall thicknesses.

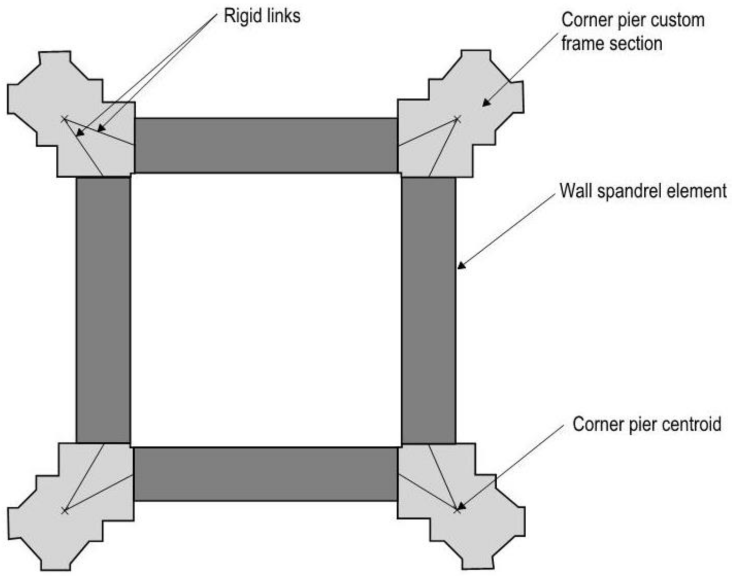

Figure 6: Plan section through the finite line/area element analytical model

2.4 Rigid link properties

As noted in Section 1.0, rigid link elements were used in the analytical model to connect the ends of the vertically discontinuous pier frame elements. Rigid link elements are frame elements with no mass and high stiffness. Rigid link elements were also used to connect the shell elements that represented the spandrel elements to the corner pier frame elements. The necessary stiffness of the rigid links was determined by progressively increasing the stiffness of the links until convergence of the fundamental periods and deflections of the structure was achieved.

2.5 Finite element mesh size selection

The sensitivity of the analytical model's dynamic characteristics to the mesh size of its finite elements was assessed by progressively refining the mesh until convergence of the model's fundamental periods was achieved. It was observed that larger element mesh sizes generally resulted in a stiffer model with a shorter fundamental period. For mesh sizes smaller than 500 mm x 500 mm, the fundamental periods of the analytical model did not change significantly; however, the analysis run time began to increase exponentially. Consequently, a maximum mesh size of 500 mm x 500 mm was ultimately selected. A summary of the results for various finite element mesh sizes is provided in Table 1.

Table 1: Variance of analytical model fundamental period with finite element mesh size

Maximum mesh dimension (mm)	East-west fundamental period (sec)	North-south fundamental period (sec)	Analysis run time (sec)
2000	0.80	0.72	45
1000	0.81	0.73	60
500	**0.83**	**0.75**	**90**
300	0.84	0.76	180
200	0.846	0.766	300

2.6 Solid finite element model

As noted in Section 1.0, a solid finite element model was developed to test the validity of the simplifications used in the finite line/area element model of the Peace Tower. The solid element model is shown in Figure 7. Its corner piers were modelled with 8-node elements. The solid finite elements were able to accurately capture the varying geometry of the Peace Tower.

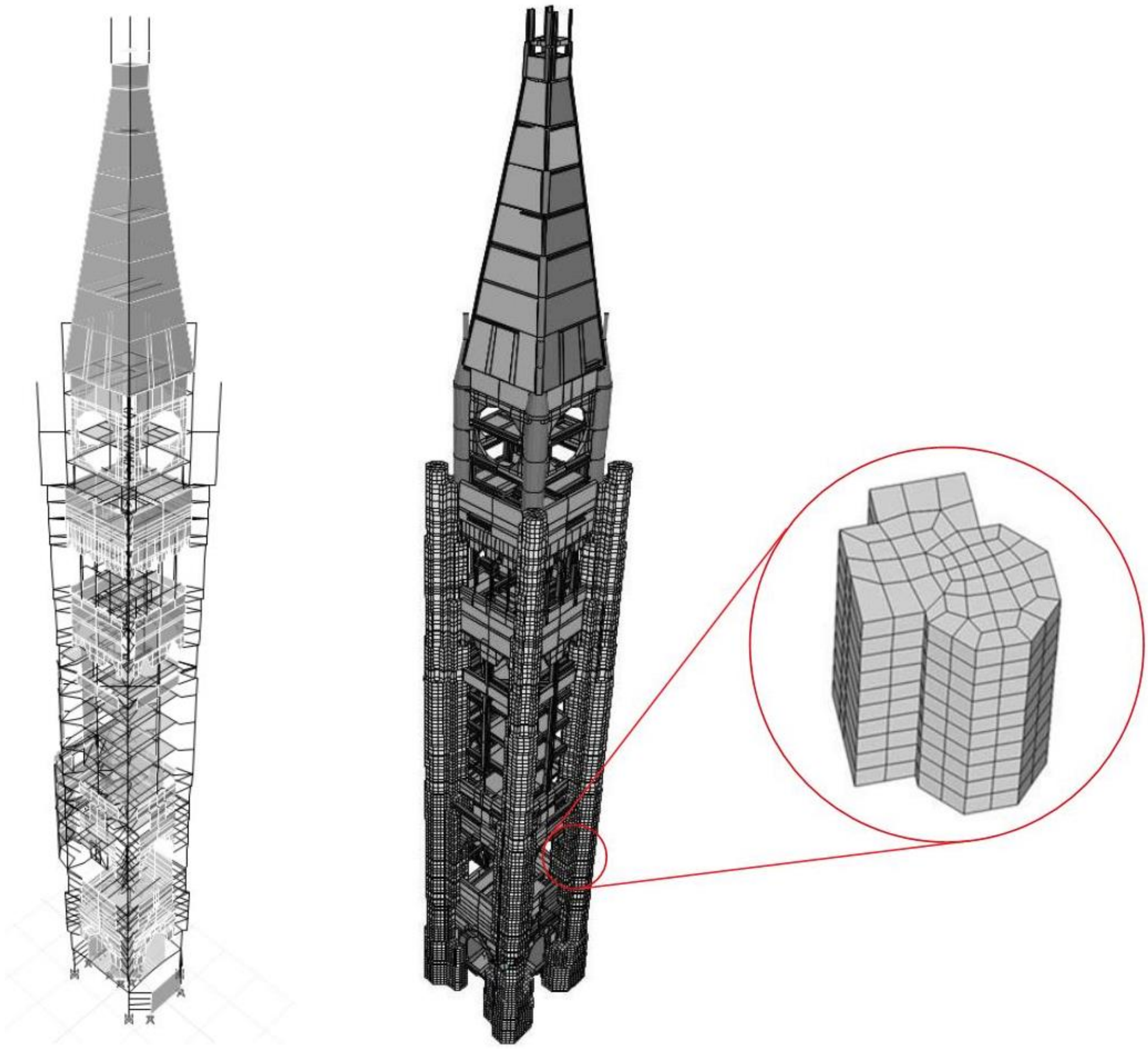

Figure 7: Peace Tower frame element model (left) and solid element model (right)

2.7 Comparison of the finite line/area model to the solid finite element model

Table 2 compares the properties of the finite line/area element model to the solid finite element model. Apart from the modelling of the pier and spandrel elements, the two models were identical in overall geometry, material properties and loading. As noted in Table 2, the weight and fundamental periods of the two models were found to differ by less than 4%, confirming that the simplified finite line/area element model, with rigid links, is an acceptable alternative to the full 3-dimensional solid finite element model of the Peace Tower. Table 2 also shows that the solid finite element model of the Peace Tower took multiple days to complete a modal analysis, whereas the simplified finite line/area element model took only minutes. For this reason, the finite line/area element model was more suitable for incorporation into a larger global model that included the adjoining Centre Block.

Table 2: Comparison of the finite area/line model and the solid finite element model

	Finite area/line element model	Solid finite element model
Weight	82 600 kN	85 900 kN
Period of 1st lateral mode in east-west direction	0.83 sec	0.84 sec
Period of 1st lateral mode in north-south direction	0.75 sec	0.74 sec
Analysis run time	1.5 minutes	70 hours

3. Dynamic calibration

3.1 Empirical vibration studies

For the purpose of determining seismic demands, the stiffness of the Peace Tower analytical model was calibrated against the results of two separate empirical vibration studies.

The first study, conducted by Sensequake in 2017, recorded the response of the Peace Tower to ambient vibrations. Sensequake's methodology, findings and conclusions are documented in their April 2018 report [3]. The periods of vibration of the Peace Tower, as determined by Sensequake, are presented in Table 3. The ambient vibration test results reported by Sensequake are consistent with the results of previous ambient vibration testing conducted by the National Research Council of Canada. Lumsdon and Sundararaj (2004) [4] reported a measured fundamental period of 0.83 seconds and Said et al. (2005) [5] reported measured fundamental periods between 0.83 and 0.91 seconds. Since periods of vibration tend to increase with seismic intensity [6], this study was used to establish an upper bound stiffness for the Peace Tower.

The second study, conducted by Lin et al. (2011) [7], recorded the response of the Peace Tower to the 2010 Val-des-Bois earthquake. This magnitude 5.0 earthquake produced moderately strong ground-shaking in Ottawa. The periods determined by Lin et al. are reproduced in Table 3. The period of the 1st lateral mode in the east-west direction was not explicitly reported by Lin et al. but was interpreted from the graph of the Fourier amplitude spectra that was presented. Table 3 indicates that, due to the higher intensity of shaking, the periods determined by Lin et al. are approximately 10-15% longer than the periods determined from Sensequake's ambient vibration tests. This study was used to establish a lower bound stiffness for the Peace Tower.

To calibrate the stiffness of the Peace Tower analytical model, a uniform stiffness modifier was applied to all pier and spandrel elements such that the analytical periods matched as closely as possible to the lower and upper bound measured periods. The stiffness modifiers necessary to achieve this result were determined to be 0.64 for the lower bound model and 0.82 for the upper bound model. The necessity to soften the analytical model (i.e. reduce its stiffness) was expected to account for the presence of shrinkage cracks and construction joints in the Peace Tower. It can be seen from Table 3 that the periods of the first seven modes of the calibrated models provide an excellent match to the periods of the empirically determined modes.

Table 3: Comparison of analytical and empirical periods for the Peace Tower

			Lower Bound		Upper Bound	
Mode no.	**Mode type**	**Analytical model periods, pre-calibration (sec)**	**Val-des-Bois earthquake empirical periods (sec)**	**Analytical model periods, post-calibration, k = 0.64 (sec)**	**Sensequake ambient vibration test empirical periods (sec)**	**Analytical model periods, post-calibration, k = 0.82 (sec)**
1	1st lateral in EW direction	0.83	1.05 (Interpreted)	1.02	0.91	0.91
2	1st lateral in NS direction	0.75	0.91	0.93	0.83	0.83
3	1st torsion	0.39	Not Reported	0.48	0.48	0.43
4	2nd lateral in EW direction	0.24	0.31	0.29	0.29	0.26
5	2nd lateral in NS direction	0.22	0.31	0.28	0.25	0.24
6	3rd lateral in EW direction	0.17	0.16	0.19	0.19	0.18
7	3rd lateral in NS direction	0.14	0.14	0.17	0.17	0.16

3.2 Val-des-Bois earthquake time history comparison

As noted in Section 3.1, the dynamic response of the Peace Tower to the 2010 Val-des-Bois earthquake was captured by seismometers, previously installed by the National Research Council of Canada [8] and was documented by Lin et al [4].

To provide further verification that the analytical model of the Peace Tower adequately captures the true dynamic characteristics of the Peace Tower, the response of the analytical model to a time history acceleration record of the 2010 Val-des-Bois earthquake was compared to the recorded response. Figure 8 shows an acceleration time history recorded at the base of the sloped roof of the Peace Tower. The response of the analytical model is also plotted for comparison. The response of the analytical model provided a close match to the actual recorded response, confirming that the analytical model adequately replicated the dynamic characteristics of the Peace Tower.

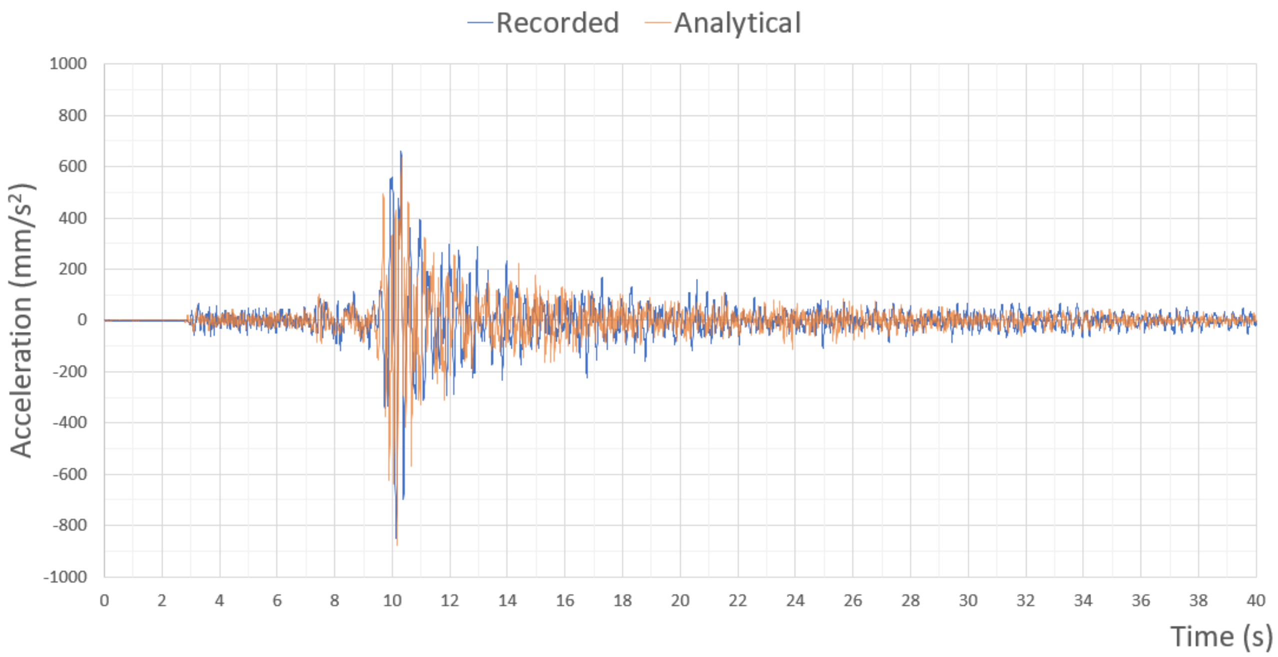

Figure 8: Peace Tower response to the 2010 Val-des-Bois earthquake – recorded vs analytical

4. Conclusions

The following observations are made regarding the approaches used to analytically model the Peace Tower of Canada's Parliament buildings:

- The simplified finite line/area element model with rigid links to accommodate offsets in structural component centroids satisfactorily replicated the dynamic response of the more complex solid finite element model.
- Application of uniform stiffness modifiers provided an excellent match between the analytically predicted modal periods and the modal periods determined from both ambient vibration testing and the recorded response of the Peace Tower to the 2010 Val-des-Bois earthquake.
- The dynamic response of the analytical model to a time-history acceleration record of the 2010 Val-des-Bois earthquake was a close match to the actual recorded response of the Peace Tower to the earthquake.
- Analysis of the simplified finite line/area element model was much less computationally onerous than the solid finite element model and unlike the solid finite element model could be incorporated into a larger global model that included the adjoining Centre Block.

5. Acknowledgements

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