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Seismic Upgrade of the Canadian Parliament Building: Part 4–Analytical Modelling

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ABSTRACT

The seismic upgrade of Centre Block will include the installation of a seismic isolation system within its basement level and beneath the Peace Tower. Similar to that required by the National Building Code of Canada for new buildings, a three-dimensional non-linear dynamic analysis was performed to establish the satisfactory performance of the seismic isolation system design. Two suites of 11 time history ground motions were assessed, including project specific vertical ground motion components. This presentation provides an overview of the analysis and a summary of the seismic isolation bearing system developed, the system base shear and displacement results. The targeted system response curve is discussed along with some additional considerations for isolated buildings located in cold climates.

Keywords: seismic upgrade, unreinforced masonry, heritage, seismic isolation, nonlinear time history analysis.

INTRODUCTION

A 3D finite element analysis model of the Centre Block and Peace Tower was created using SAP2000. Figure 1 illustrates the 3D computational model. The model was used to determine the building's fundamental period, to perform an equivalent static and dynamic analysis, and to test the sensitivity of the analysis results to specified material properties.

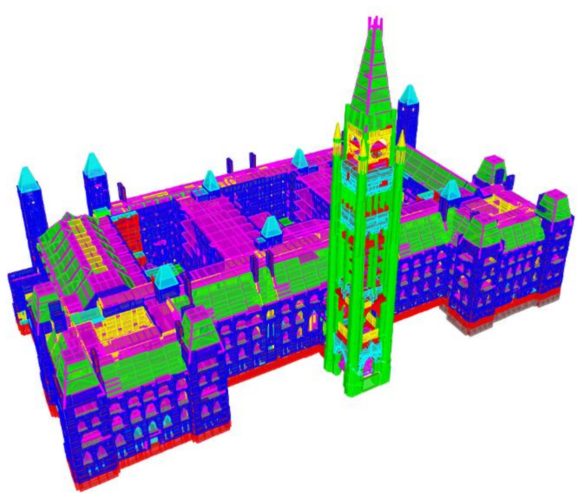


Figure 1. Centre Block and Peace Tower Finite Element Model

The walls and floors were modelled using finite element shell objects. Beam and columns were modelled with frame elements. Reduced element stiffness to account for cracking of the concrete and masonry sections was incorporated through use of element stiffness modifiers. The stiffness modifiers applied to the properties of the shell elements used to model the masonry walls were determined from nonlinear studies of individual walls sections. An estimate of the potential range of the Centre Block's dynamic response was obtained using upper and lower bound material properties. The fundamental periods given by the FE model were validated by the ambient vibration test results.

UNIFORM HAZARD RESPONSE SPECTRUM

Figure 2 shows the design Uniform Hazard Spectrum (UHS) in accordance with the NBCC 2020. Using a base isolation system, the effective period of the combined Centre Block and Peace Tower structures can be increased from approximately 0.2 second for Centre Block and 0.9 second for the Peace Tower to approximately 3 seconds resulting in a significant reduction in base shear and superstructure forces.

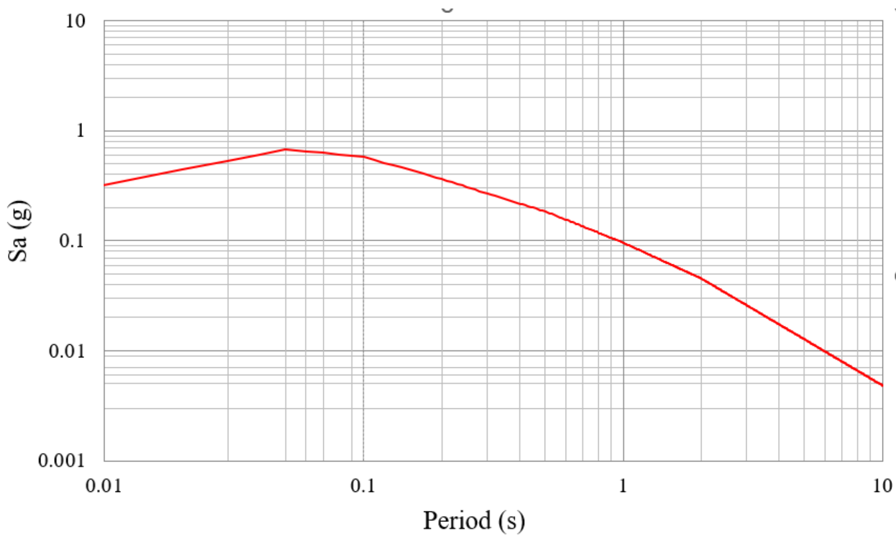


Figure 2. NBCC 2020 design UHS for Centre Block site.

Seismic Isolation System

The initial, schematic design of the Centre Block-Peace Tower seismic isolation system comprised approximately 580 isolation bearings (Figure 3), consisting of a combination of four different sizes of natural rubber bearings (NRB), four different sizes lead-rubber bearings (LRB) and one size of sliding bearings (SB) (note: detailed design is currently ongoing, refining the quantities and sizes of the different types of bearings)

The isolators were placed along the original structure gravity load path to minimize redistribution of vertical loads. The size and properties of the isolators were tuned to suit the gravity loads supported by them, and to produce the system properties required to achieve the target base shear and post-yield structural period. The yield strength and pre- and post-yield stiffness characteristics of the different types of isolation bearings were tuned to provide a target mean base shear of 3% of the seismic weight at the design displacement. The system curve for the isolation system was obtained by performing a nonlinear pushover analysis on the isolated structure.

Figure 4 compares the Upper Bound (UB) and Lower Bound (LB) system curves using the upper- and lower-bound properties of isolators with the nominal system curve using nominal isolator properties. The initial yield of the isolation system as indicated by the LB isolator model system curve is approximately 1.5 times the wind load determined from wind tunnel tests. The displacement of the LB isolator model under the design wind load is about 2.4 mm which is only about one-third of the 7.6 mm NBCC 2020 limit of 1/500 of the least storey height above the isolation plane.

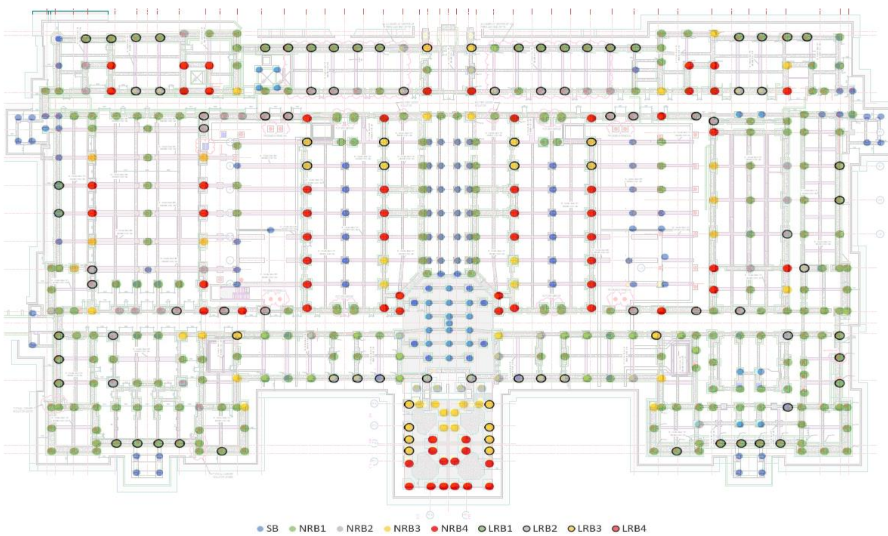


Figure 3. Plan layout of Centre Block-Peace Tower seismic isolation system.

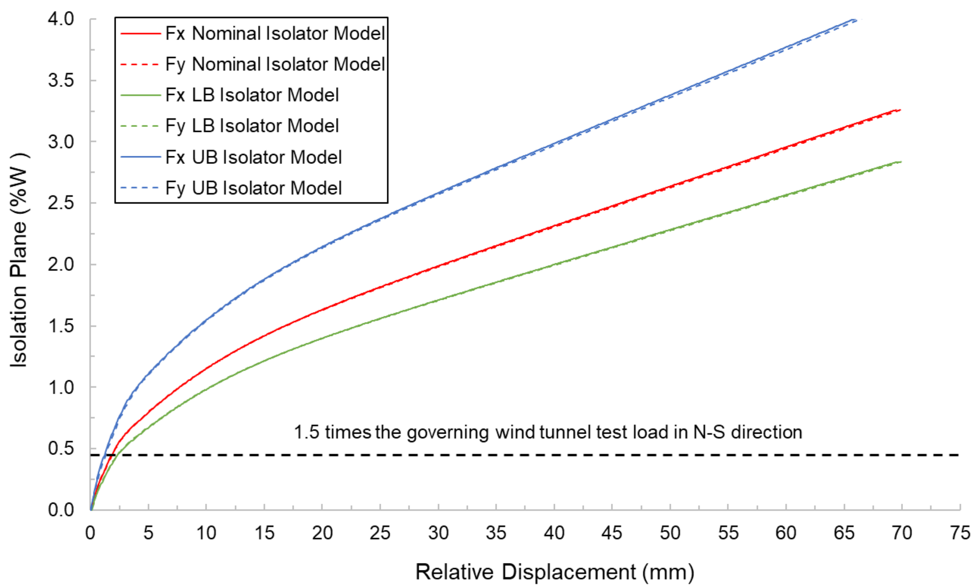


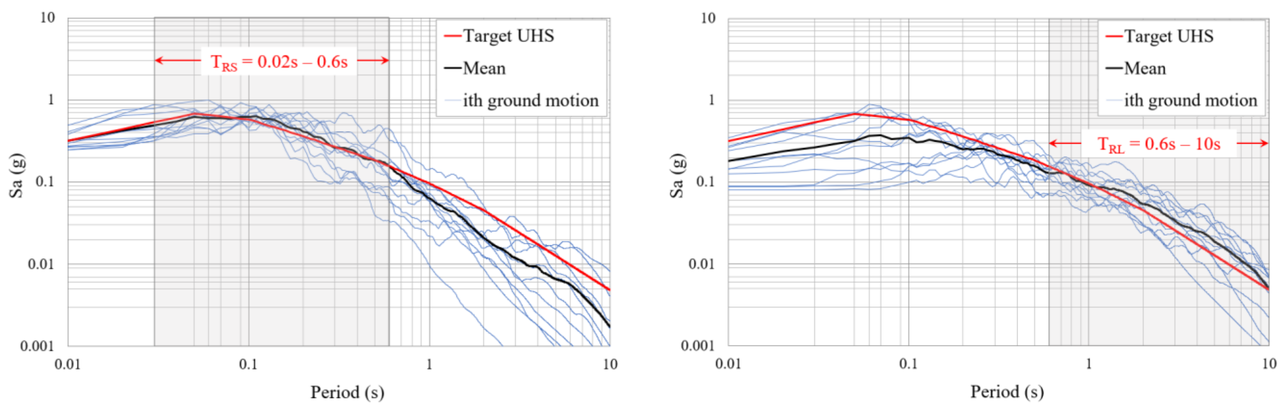
Figure 4. Isolation system force-displacement curve obtained from nonlinear pushover analysis.

EARTHQUAKE DESIGN SPECTRUM AND TIME HISTORIES

The UHS for Centre Block, with 2% probability of exceedance in 50 years, was obtained from Canada's 6th generation seismic hazard model as used in NBCC 2020 [1] for the project site with Vs30 = 1976 m/s. The period of the isolated building considering the post-yield stiffness is about 3 seconds. Therefore, the period range for scaling of ground motion is T_R = 0.6s – 4.5s according to the NBCC 2020 Article 4.18.19.4(c). However, the period range was extended to T_R = 0.02s –10s to cover a wider range for scaling of ground motions. The lower bound was specifically lowered to a period such that the period range achieves 90% of mass participation in all three directions including horizontal and vertical directions.

In accordance with the NBCC 2015 Commentary J (NBCC 2020 Commentary J not yet published), the period range of scaling T_R was separated into two segments. Each segment is covered by an appropriate suite of ground motions considering the dominant earthquake magnitude-distance combinations revealed by site-specific seismic hazard disaggregation. For this purpose, T_R was separated into a short-period segment (T_{RS} = 0.02 second < T < 0.6 second) to select records from small magnitude nearby earthquakes and a long-period segment (T_{RL} = 0.6 second < T < 10 seconds) to select records from larger magnitude distant earthquakes.

Two suites of 11 records each, compatible with the short-period and long-period parts of the UHS were developed. The ground motions were linearly scaled so that the mean of the ground motion geometric means stayed above 90% of the UHS in the period range of interest for each set, in accordance with 2015 NBCC Commentary J. Figure 5 compares the mean of the selected motions with the target UHS in the short and long-period ranges.

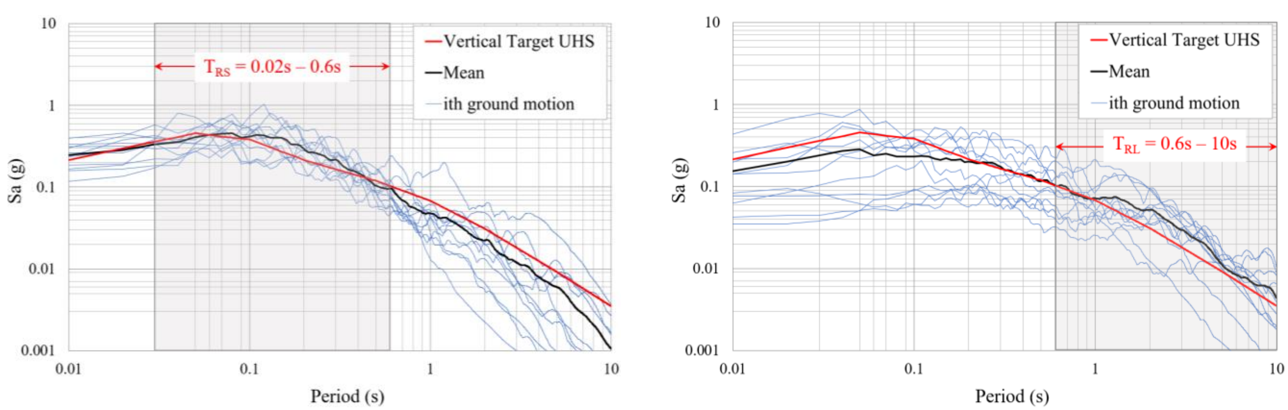


(a) *(b)*

Figure 5. Horizontal Geometric Mean Spectral acceleration of short-period (a) and long-period (b) sets.

According to NBCC 2015 Commentary J, the vertical ground motions should be compatible with the vertical design spectrum. For this project, a site-specific vertical design spectrum was developed based on vertical to horizontal spectra relationship from [2]. The scaling of the vertical components of the records was decoupled from the horizontal components.

Scaling factors for the vertical components, independent from horizontal component scaling factors, were developed to make the vertical components compatible with the vertical target spectrum in accordance with NBCC 2015 Commentary J as shown in Figure 6.



(a) *(b)*

Figure 6. Vertical spectral acceleration of short-period (a) and long-period (b) sets.

NONLINEAR TIME HISTORY ANALYSIS

Base Shears and Maximum Isolators Displacements

SAP2000 features both direct integration and Fast Nonlinear Analysis (FNA) methods for performing nonlinear time history analysis. The FNA approach was found to be the most efficient and best-suited method for the project. However, to fine-tune the parameters of the nonlinear analysis, an extensive sensitivity study was carried out whereby the influence of the number of Ritz modes used in the FNA analysis and the inclusion of the vertical component of the ground motion on the demands induced at the isolation plane and in the superstructure were investigated.

In addition, direct integration time history analysis was performed for a few ground motions and the results were used as a benchmark to which the FNA results were compared to ensure consistency and convergence of the two different analysis approaches. Different iterations of the model setup with the FNA approach were tested, with increasing numbers of Ritz modes. It was found that 7000 Ritz modes in the FNA were required to provide results that matched those given by the direct integration analysis method.

A modal damping of 0.5% was assigned to the isolated modes and 2% to all other modes of the structure. A summary of the mean, standard deviation (SD), mean + SD, and maximum total forces and displacements obtained at the isolation plane of Centre Block and the Peace Tower for the short-period and long-period time history sets using nominal isolator properties are presented in Table 1. The total base shear and displacement demands at the isolation plane were governed by the long-period ground motion set.

As shown in Table 1, the mean + SD base shear is about 1.9% and 3.3% of the isolated seismic weight for the short-period and long-period ground motion sets, respectively. The larger base shears resulting from the long-period set are close to the 3%W target base shear. The mean + SD displacement at the isolation plane is about 33mm and 95mm for short-period and long-period ground motion sets, respectively. The analyses were also performed using LB and UB isolator properties and it was confirmed that the total shear and maximum displacement responses are within acceptable limits.

Table 1. Comparison of mean, SD, mean + SD, and maximum total forces and displacements at the isolation plane using short-period and long-period sets of time histories.

Time Histories Set	Ground Motions	Total Forces at Isolation Plane			Displacement at Isolation Plane		
		Fx (% W)	Fy (% W)	Fz (% W)	X (mm)	Y (mm)	SRSS (mm)
Long-Period	**Mean**	**2.3**	**2.3**	**10.4**	**45**	**47**	**61**
	SD	0.6	0.9	5.2	20	31	34
	Mean + SD	**3.0**	**3.3**	**15.5**	**66**	**78**	**95**
	Maximum	3.8	3.8	19.9	87	105	112
Short-Period	**Mean**	**1.2**	**1.4**	**21.5**	**15**	**18**	**22**
	SD	0.5	0.5	12.2	11	9	11
	Mean + SD	**1.8**	**1.9**	**33.7**	**26**	**27**	**33**
	Maximum	2.3	2.1	43.2	40	35	48

Superstructure Forces

One of the main objectives of the base isolation scheme is to significantly reduce lateral seismic demands on the various components of the superstructure including the masonry walls, piers, and spandrel beams as compared to a fixed base structure.

The shears induced at the base of 126 individual walls in Centre Block were determined for the isolation system with nominal, LB and UB isolator properties. The results were compared to the capacity of the walls obtained from separate pushover analyses of the individual wall segments using VecTor2 [3]. The demand for only a small number of walls exceeded the estimated capacity. One key observation made during the time-history analyses of the seismically isolated structure was the relatively significant increase in the in-plane shear demands of the individual wall segments above the isolation plane when the vertical ground motion component is included. This is discussed in more detail in a companion paper [4].

COLD WEATHER CONSIDERATIONS

In cold-weather climates, such as Ottawa, the adverse effects of snow build-up around the perimeter of the building and ice adhesion at exposed sliding surfaces of the moat covers can contribute to the breakaway resistance of the isolation system with the potential to increase the breakaway resistance beyond acceptable limits (the building behaves as a fixed base building until breakaway occurs). This can be especially problematic for base-isolated buildings in regions of low to moderate seismicity that have low target design base shears, such as this project with a target base shear of some 3%W. Snow removal, either manually or through snow-melt systems (such as heat tracing or hydronic piping), mitigates the adverse effects of snow. Reducing contact areas at sliding interfaces, employing surfaces with low ice adhesion strengths, providing dehumidification within certain portions of the moat, and heat tracing at specific sliding surfaces are effective mitigation measures to reduce ice adhesion breakaway resistance. All these are being considered for the final design of the various exterior sliding joint details. This is discussed in more detail in a companion paper [5].

CONCLUSION

This paper presents some of the key aspects of the analysis of the seismic isolation system for the seismic upgrade of the Canadian Parliament Centre Block and Peace Tower. A detailed 3D finite element model of Center Block and Peace Tower was developed to perform nonlinear time history analysis. Two sets of ground motion records scaled to the short-period and long-period ranges of the design spectrum were used to the analysis. The analysis results have shown that seismic isolation significantly reduces the lateral seismic demands on the various components of the superstructure as compared to the existing fixed-base configuration.

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