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Impact of Vertical Ground Motions on Base Isolation Seismic Upgrade of the Canadian Parliament Building

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ABSTRACT

The Centre Block of Canada's Parliament, a prominent and iconic heritage building, is currently undergoing an extensive restoration. Constructed over a century ago, Centre Block consists of a 6-story structure with predominantly stone and brick walls, steel columns, and unreinforced concrete wall foundations, connected to a 92 m tall Peace Tower supported by unreinforced concrete piers, both of which are at high seismic risk. Base isolation is being implemented for the seismic upgrade of Centre Block as a cost-effective retrofit method to reduce the seismic demand, enhance likelihood of achieving business continuity, and preserve the heritage characteristics of the building. The base isolation system comprises approximately 580 different types of isolators including rubber and flat slide bearings.

Nonlinear time history analyses were conducted using a detailed three-dimensional analytical model to establish the isolation properties in compliance with the 2020 National Building Code of Canada (NBCC 2020). Two sets of 11 ground motion records were employed for the analyses, with one set scaled for the short-period range of the design spectrum and the other for the long-period range. A site-specific vertical target spectrum was developed, and scaling factors for the vertical ground motion component were determined independently from the horizontal components to ensure compatibility with the vertical spectrum.

This paper investigates the impact of the vertical component of ground motions on the shear demands of superstructure walls and piers in a base-isolated structure. The results highlight a significant increase in shear demands for the superstructure walls due to the vertical component of short-period ground motions, a response not necessarily attenuated by the isolation system. However, despite this increase, the analysis demonstrates that the base-isolation system effectively reduces the induced base shear in the walls compared to conventional retrofit methods for fixed base structures.

Keywords: base isolation, seismic retrofit, heritage building, vertical ground motion

INTRODUCTION

The Centre Block of Canada's Parliament (Figure 1), located on Parliament Hill in Ottawa, is presently undergoing an extensive restoration. This architectural marvel encompasses six above-ground stories and a basement level. Built between 1916 and 1920, it is composed of brick, stone masonry, steel, and concrete. The iconic Peace Tower, integrated into the structure, was constructed between 1919 and 1927 and stands approximately 92 meters tall. The Peace Tower consists of unreinforced concrete walls with an outer layer of stone masonry, supported by unreinforced concrete piers. Similar to many buildings constructed in Canada during the early 20th century, Centre Block and the Peace Tower were not designed or constructed with consideration for seismic loads [1]. A seismic assessment of these structures revealed the potential for significant damage to their walls, floors, and roof diaphragms under the seismic loads specified by the National Building Code of Canada (NBCC). During the schematic design phase, it was determined that a conventional seismic upgrade strategy would be inadequate in fully preserving Centre Block's heritage finishes and maintaining its business continuity.

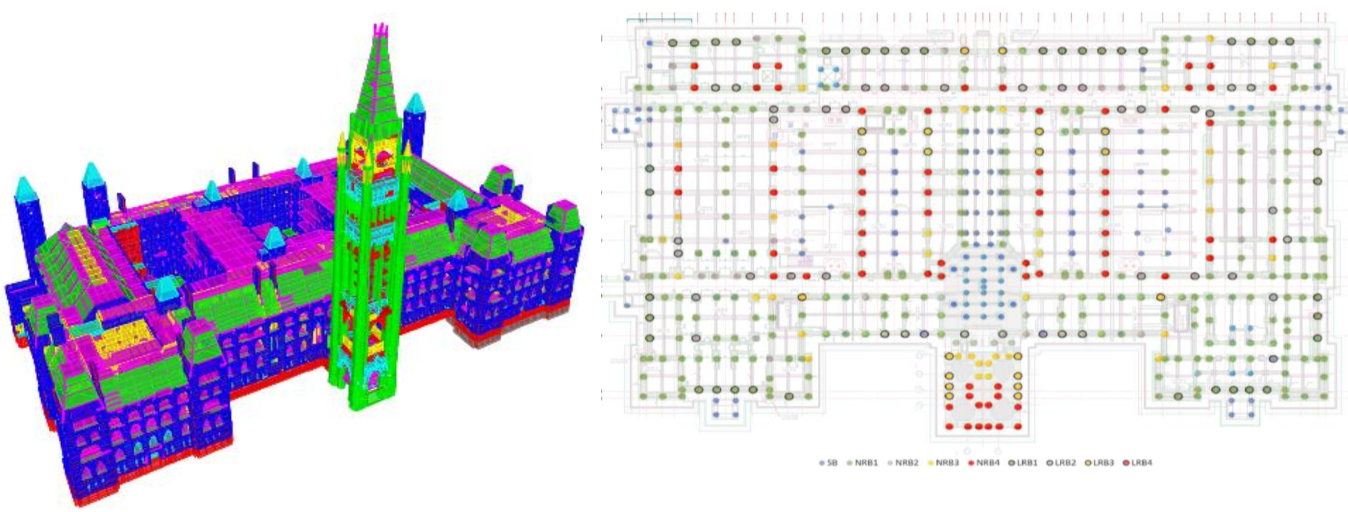
Figure 1. Centre Block and Peace Tower (Library behind).

A seismic upgrade approach incorporating base isolation has been developed to effectively reduce seismic demands on the building and enhance the likelihood of maintaining business continuity. This approach not only preserves the heritage characteristics of the buildings but also minimizes interventions required for the superstructure and significantly reduces the need for seismic restraint of non-structural components. By implementing a base isolation system, the period of the combined Centre Block and Peace Tower structures can be extended to 3 seconds, resulting in a substantial decrease in base shear and forces imposed on the superstructure elements.

ANALYTICAL MODELING

The 3D finite element model of the Centre Block and Peace Tower, shown in Figure 2(a), was generated using SAP2000 software. Stiffness modifiers were applied to the properties of the shell elements representing the masonry walls. These modifiers were determined through comprehensive nonlinear analyses of individual wall sections conducted using VectTor2 software [2]. The structural periods obtained from the numerical model closely matched those derived from ambient vibration testing and the recorded response to the Val-des-Bois earthquake [3, 4, 5].

The isolation system originally comprised of approximately 580 isolators, including natural-rubber bearings, lead-rubber bearings, and flat sliding bearings. The layout of the isolators is illustrated in Figure 2(b). The initial yield of the isolation system is approximately 1.5 times the wind load determined from wind tunnel tests. The displacement of the isolated 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.



(a) *(b)*

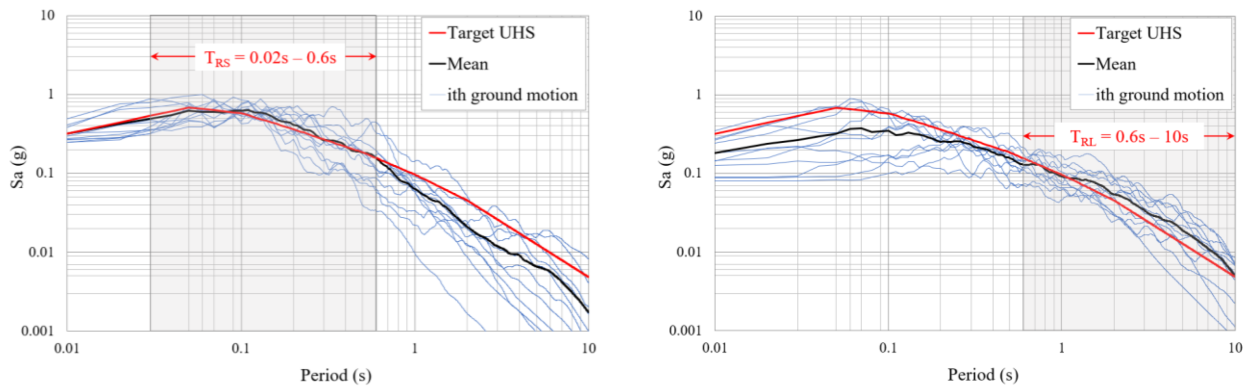
Figure 2. (a) Centre Block and Peace Tower Finite Element Model and (b) Isolator layout.

EARTHQUAKE DESIGN SPECTRUM AND TIME HISTORIES

The Centre Block project site is located on the northern edge of the Ottawa-Bonnechere graben, in an area of intraplate earthquake activity. Despite its distance from major plate boundaries, the region underwent significant extension during the late Proterozoic due to the rifting and opening of the Iapetus Ocean [6]. Reactivation of this ancient rift is thought to be the cause of much of the present-day earthquake activity in the Saint Lawrence, Ottawa-Bonnechere and Saguenay grabens.

Horizontal spectrum and time histories

The Uniform Hazard Spectrum (UHS) for Centre Block, with a 2% probability of exceedance in 50 years, was derived from Canada's 6th generation hazard models as utilized in NBCC 2020 [7]. The UHS was obtained for the project site with a V_{s30} value of 1976 m/s. According to NBCC 2015 Commentary J (NBCC 2020 Commentary J not yet released), the target UHS was divided into two sections: a short-period range (T_{RS} = 0.02s < T < 0.6s) and a long period range (T_{RL} = 0.6s < T < 10s). Two sets of ground motion records, comprising 11 records each, were developed to align with the short-period and long-period segments of the UHS. The ground motions were linearly scaled to ensure that the mean of the horizontal ground motion geometric means remained above 90% of the UHS in the relevant period range for each set, in accordance with the 2015 NBCC Commentary J guidelines. Figure 3 presents a comparison between the mean values of the selected motions and the target UHS in the short and long-period ranges.



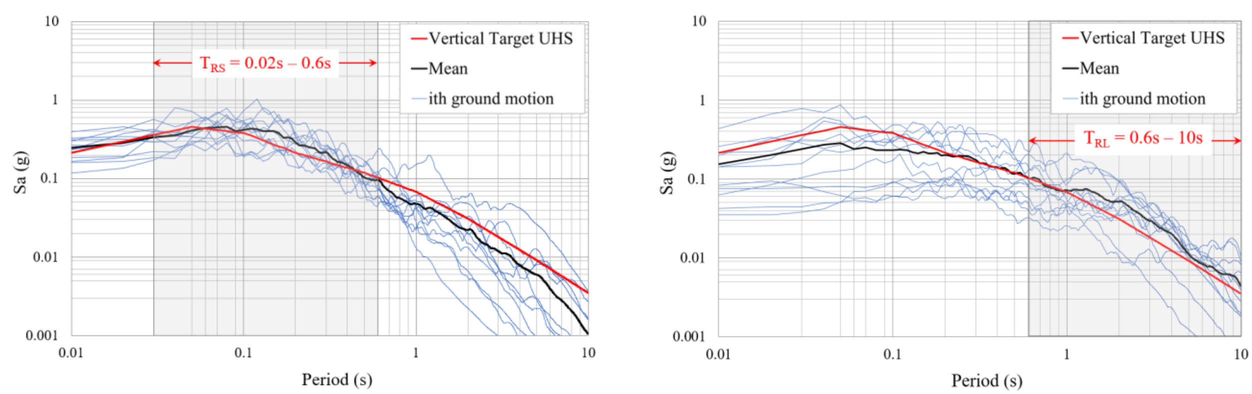
(a) *(b)*

Figure 3. Horizontal Spectral acceleration of (a) short-period and (b) long-period sets.

Vertical spectrum and time histories

According to the NBCC 2015 Commentary J, it is essential to ensure compatibility between vertical ground motions and the vertical design spectrum. In this project, a site-specific vertical design spectrum was developed to meet this requirement. The Vertical to Horizontal (V/H) spectral ratio from [8] was employed by multiplying it with the horizontal target spectrum, yielding the vertical target spectrum.

Vertical component scaling was decoupled from the horizontal components, allowing for the independent development of scaling factors specific to the vertical components. This was done to ensure their compatibility with the vertical target spectrum, following the guidelines outlined in NBCC 2015 Commentary J. The results of this approach are shown in Figure 4.



(a) *(b)*

Figure 4. Vertical spectral acceleration of (a) short-period and (b) long-period sets.

NONLINEAR TIME HISTORY ANALYSIS

Base Shears and Maximum Isolators Displacements

Based on the model's size and the limited presence of nonlinearities in isolators, it was determined that the Fast Nonlinear Analysis (FNA) method emerged as the most efficient and suitable approach for analyzing the base-isolated Centre Block and Peace Tower structures. After conducting an extensive sensitivity study and comparing it with direct integration time history analysis, it was determined that a total of 7,000 Ritz modes were necessary in the FNA approach.

Two suites of short and long-period ground motion sets were used for the FNA analyses. The FNA method utilized 7000 Ritz modes, with 0.5% damping assigned to the isolated modes and 2% damping assigned to all other modes of the structure. Table 1 presents a summary of the average total forces and displacements acquired at the isolation plane of the Centre Block and Peace Tower using nominal isolator properties, considering both the short and long-period time history sets.

To better comprehend the influence of vertical ground motions, two sets of analyses were conducted for each record set:

1) The analysis included all three ground motion components, incorporating both horizontal and vertical time histories (With Vertical).
2) The analysis solely considered horizontal ground motions, excluding the vertical component from the analysis (Without Vertical).

The analysis indicates that the presence of the vertical component in the ground motions has minimal influence on the total lateral shear (Fx and Fy) and displacement demands at the isolation plane. However, it is worth noting that the vertical force (Fz) on the base isolation plane experiences an increase of approximately 10% W and 22% W for the long and short-period ground motion sets, respectively. While the long-period set of motions primarily governs the lateral shear demands and displacements at the isolation plane, the vertical demand is predominantly influenced by the short-period set of motions.

Table 1. Comparison of mean total forces and displacement at the isolation plane using short and long-period sets of time histories, with and without vertical ground motion component.

Time Histories Set	Ground Motions Component	Total Force at Isolation Plane			Displacement at Isolation Plane		
		Fx (% W)	Fy (% W)	Fz (% W)	X (mm)	Y (mm)	SRSS (mm)
Long Period	With Vertical	2.3	2.3	10.4	45	47	61
	Without Vertical	2.3	2.3	0.1	45	47	61
Short Period	With Vertical	1.2	1.4	21.5	15	18	22
	Without Vertical	1.2	1.4	0.1	15	18	22

Superstructure Forces

The primary objective of the base isolation scheme is to achieve a substantial reduction in lateral seismic demands on various components of the superstructure, including masonry walls, piers, and spandrel beams, in comparison to a fixed base structure. This objective has been successfully achieved. The following discussion focuses on the variations in the reduced demands, which remain significantly lower than those observed in a fixed base structure.

The shear forces exerted at the base of 126 individual walls in the Centre Block were assessed using the isolation system, considering nominal, lower-bound, and upper-bound isolator properties. The obtained results were then compared to the capacity of the walls, which were determined through separate pushover analyses of the individual wall segments using VecTor2 [2]. It was observed that the demand exceeded the capacity in only a small number of walls, necessitating further refined pushover analyses and assessment to be conducted.

One notable observation during the time history analysis of the base isolated structure was the relatively substantial rise in the in-plane shear demands of the individual wall segments located above the isolation plane when the vertical component of the motion was incorporated in the time history analysis, alongside the two horizontal components. However, despite this notable increase, there were no changes observed in the total base shear and displacement demands at the isolation plane and individual isolators, as indicated in Table 1.

To assess the shear demands in the superstructure walls, section cuts were placed at the base of 126 individual walls throughout the entire structure, specifically above the isolation plane diaphragm. Peak in-plane shear force demands and maximum in-plane drift demands along the height of the walls above the isolation plane were outputted from the model using short and long-period set ground motions. Furthermore, forces were extracted from analyses conducted with and without the vertical ground motion component, aiming to assess the impact on shear demands induced in the superstructure walls.

Figure 5 and Figure 6 show the ratio of mean wall base shears when considering the contribution from the vertical time history record components compared to analyses conducted without them. Figure 5 illustrates the ratios for the long-period ground motion set, while Figure 6 presents the ratios for the short-period ground motion set. These ratios were calculated for 126 individual wall segments across the superstructure. Notably, Figure 5 demonstrates that, with a few exceptions, the contribution of the vertical component in the long period ground motion set does not have a significant impact on the induced base shear.

Nevertheless, as shown in Figure 6, the inclusion of the vertical component in the short period ground motion set leads to a significant rise in induced base shear demands. On average, the shear demands in the 126 walls experience an approximately 85% increase when considering the vertical component. This additional induced shear demand primarily occurs at frequencies above 10 Hz, which closely corresponds to the vertical frequency of vibrations in individual floors as well as the global vertical mode of the isolated structure.

Notably, the short period ground motion set, scaled in the short period range between 0.02 and 0.6 seconds, contains high accelerations within this frequency range. Consequently, the impact of the vertical component in the short period ground motion set on vertical vibration and the subsequent increase in induced shear demands on the walls is more pronounced compared to the long period ground motion set. The long period set exhibits lower spectral amplitudes in the high-frequency range, reducing the impact of the vertical component in that frequency range.

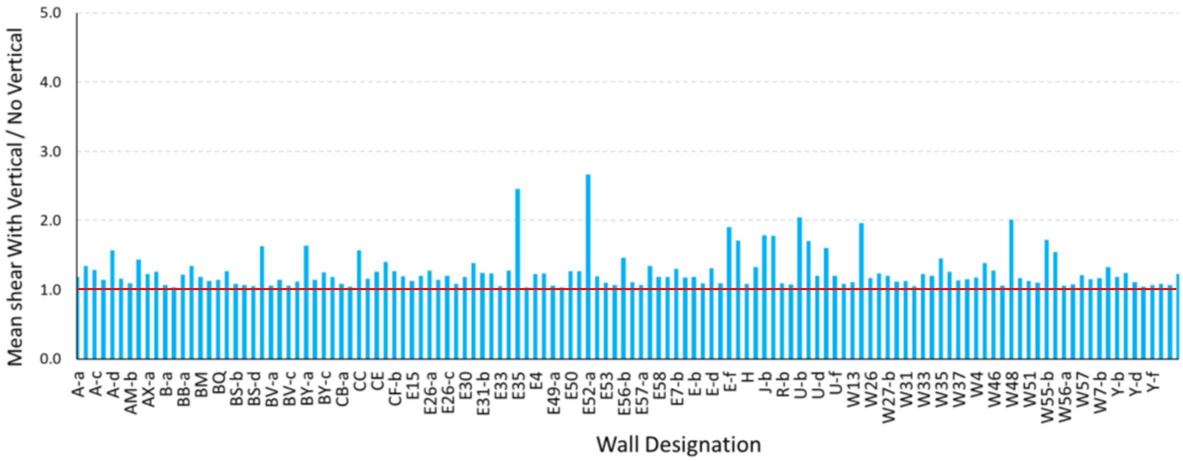


Figure 5. Ratio of walls mean base shear with vertical ground motion component to mean base shear without vertical component for 126 walls using long-period set ground motions.

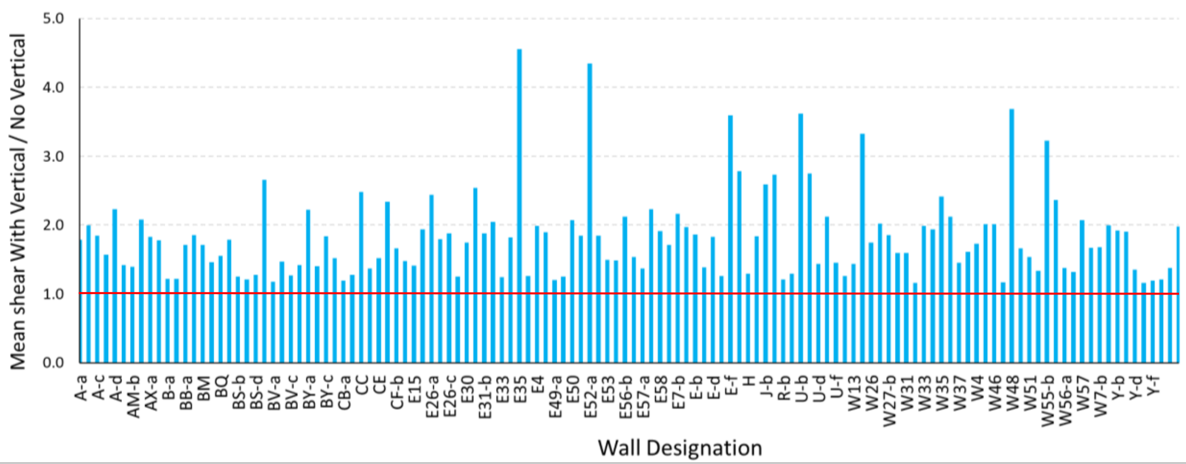


Figure 6. Ratio of walls mean base shear with vertical ground motion component to mean base shear without vertical component for 126 walls using short-period set ground motions.

CONCLUSIONS

This paper provides a brief overview of the analyses conducted for the base isolation seismic upgrade of Centre Block, an iconic heritage building situated on Parliament Hill in Ottawa, Canada. The study demonstrates the substantial reduction in lateral seismic demands on various superstructure components, such as masonry walls, piers, and spandrel beams, achieved through the implementation of a base isolation scheme, as compared to a fixed base structure.

Furthermore, the analysis reveals the noteworthy increase in induced shear demands on the superstructure walls due to the inclusion of the vertical component in the short period ground motion set. These additional induced shear demands primarily occur within the frequency range associated with the vertical vibration frequency of individual floors and the global vertical mode linked to the overall vertical stiffness of the isolation system.

Despite this increase, it is important to highlight that the base isolation system significantly reduces the induced base shear in the walls compared to conventional retrofit methods applied to fixed base structures. Consequently, the majority of walls experience shear forces below their elastic capacity, as determined through nonlinear pushover analysis of individual walls.

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REFERENCES

[1] Huiskamp J, Carson D, Arnold D (2015). "Masonry stiffness for the seismic assessment of the Centre Block on Parliament Hill". *In Proceedings of the 11th Canadian Conference on Earthquake Engineering*, Victoria, BC.
[2] Wong P, Vecchio FJ (2013). "VecTor2 and Formworks Manual". University of Toronto, Department of Civil Engineering Canada.
[3] Lin L, Adams J, Paquette J, Glazer R, Duchesne D (2011). ÈDynamic characteristics of three major towers on Parliament Hill, Ottawa, from recorded vibrations during the Val-des-Bois". *In Proceedings, Annual Conference-Canadian Society for Civil Engineering*, Ottawa, ON.
[4] Kolaj, M. and Adams, J. (2021). "Dynamic characteristics of Canada's Parliament Hill towers from ambient vibrations and recorded earthquake data". *Canadian Journal of Civil Engineering*; 48(1), 16-25.
[5] Lin L, Adams J (2011). "Engineering characteristics of ground motion records of the Val-des-Bois". In *Proceedings, Canadian Society for Civil Engineering Annual Conference*, Ottawa, ON.
[6] Mazzotti, S., T. S. James, J. Henton, and J. Adams (2005). "GPS crustal strain, postglacial rebound, and seismic hazard in eastern North America: The Saint Lawrence valley example." *Journal of Geophysical Research*, 110(B11).
[7] Kolaj, M., Halchuk, S., Adams, J. and Allen, T.I. (2020). "Sixth generation seismic hazard model of Canada: input files to produce values proposed for the 2020 National Building Code of Canada." Geological Survey of Canada Open File 8630, 2020, 15 p.
[8] Gülerce, Z, Abrahamson, NA. (2011). "Site-specific design spectra for vertical ground motion". *Earthquake Spectra*; 27(4), 1023-1047.