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Base Isolation Seismic Upgrade of a Heritage Building at Lord Strathcona Elementary School

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ABSTRACT

The Lord Strathcona Elementary School, located in Vancouver, British Columbia consists of three heritage buildings, with the oldest constructed in 1897. The seismic retrofit of the 1897 three-storey load bearing brick and stone building used seismic isolation (base isolation) to achieve an immediate occupancy post-earthquake performance, as well as providing post-earthquake heritage preservation. This project, completed in early 2017, represents the first base isolated building in Canada. Unique is that the isolation plane is above ground requiring no moat. 3D computer analyses followed new provisions for seismically isolated buildings, introduced in Canada in the National Building Code (NBC), 2015 edition. This involved analyses of three different suites of earthquake ground motions: 11 subduction records, 5 crustal records, and 5 intraslab records. The seismic demand on the brick walls above the isolation plane was reduced to approximately 0.15 g, thus requiring effectively no structural upgrades above the isolation plane. This paper outlines the following:

- “Conventional” retrofit options considered and their costs.
- Isolation scheme approximately same cost as conventional scheme, but offered superior post-earthquake performance.
- Material testing carried out to determine structural parameters.
- Selection/scaling of ground motions for analyses.
- 3D non-linear analyses per NBC 2015 provisions.
- Comparison of friction pendulum vs lead rubber bearing options for isolation system; full design for each carried out.
- Construction highlights, challenges, lessons learned including: total separation of structure above the isolation plane, from that below, connected only by 30 new isolators involving a completely new vertical load path; multi-stage load transfer to the new isolators using flat jacks, achieved with less than 3 mm vertical movement at the isolation plane, avoiding damage to the brittle structure; and custom details of mechanical, electrical and architectural components to accommodate the predicted 250 mm lateral movement at the isolation plane.

Keywords: seismic upgrade, base isolation, heritage building, 3D non-linear analyses, earthquake ground motions

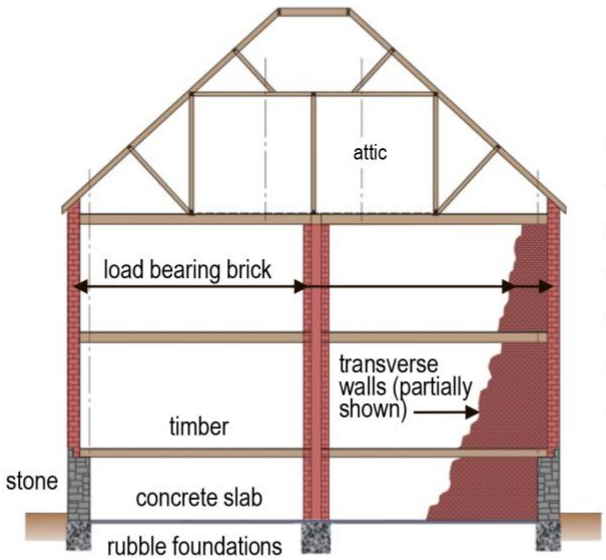
INTRODUCTION

Vancouver’s Lord Strathcona Elementary School has been operating since 1891, one of the oldest elementary schools in British Columbia. As part of the Ministry of Education’s (MEd’s) Seismic Mitigation Program four heritage buildings at the school were assessed and rated as High seismic risk, with seismic upgrades carried out for three buildings retained for school purposes. This paper focusses on the Class A heritage, 1897, three-storey timber/brick/stone classroom building where the seismic upgrade was achieved using base isolation, the first time this seismic structural technology has been used in Canada for an occupied building.

Critical design aspects for the project’s success included: total separation of the structure above the isolation plane, from that below, connected only by 30 new isolators involving a completely new vertical load path; multi-stage load transfer to the new isolators using flat jacks, achieved with less than 3mm vertical movement of the original constructed level, avoiding damage to the brittle structure; and custom details to accommodate the predicted 250 mm lateral movement at the isolation plane.

BUILDING DESCRIPTION

The building has two floors plus a basement and an unused attic; there is approximately 1,800 m^2 of total usable floor area (not including the attic). The original vertical load bearing system consisted of unreinforced brick walls on basement stone walls on rubble foundations at the exterior perimeter, four interior transverse brick walls, as well as a main longitudinal interior brick wall spline. The roof and floors consisted of wood framing of heavy timber joists and diagonal shiplap. The main aspects of the original structure are illustrated in Figure 1. The brick and mortar was categorized as 'soft and weak'. Some exterior joints had been repointed in the past with strong mortar.



- Basement exterior walls – 600 mm thick stone;
- First floor exterior walls – 4 wythe 450 mm thick solid brick;
- Second floor exterior walls – 3 wythe 330 mm thick solid brick;
- Upper attic walls – 3 wythe 330 mm thick solid brick;
- Floor framing – 75 mm x 385 mm joists at 400 mm;
- Floor sheathing – diagonal shiplap with one layer of plywood;
- Interior spline brick wall – 1.1 m wide, made of 2 wythe brick (225 mm) on each side of a hollow duct space (approximately 685 mm).

Figure 1. Cross section of original structure and description of elements.

CONCEPTUAL DESIGN OPTIONS

Two different conceptual designs were developed for the seismic upgrade of this building: a 'conventional' upgrade scheme, and a base isolation upgrade scheme.

Conventional Upgrade Scheme

The conventional upgrade scheme consisted of the following items:

- New full-height concrete moment frames, in both the longitudinal and transverse directions, to replace all interior load bearing brick walls; including new foundations;
- Demolishing the remaining interior brick partition walls and replacing with stud walls;
- Diaphragm upgrade for all floors using horizontal steel bracing underneath;
- Diaphragm upgrade for roof using plywood;
- Out-of-plane restraint of exterior brick walls using steel HSS spanning between floors;
- New plywood shear walls in attic space.

Seismic Isolation Upgrade Scheme

Seismic isolation (also called base isolation) is an innovative design technique which consists of an isolation system (collection of isolators) with low horizontal stiffness, high vertical stiffness, high energy dissipation, re-centering capability, installed at an 'isolation plane' between the foundation and the superstructure. For seismic upgrades, the concept typically requires that the original vertical load path be modified to have all vertical load supported only by the new isolators. Seismic isolation very significantly reduces the lateral earthquake demand to the structure above the isolation plane such that the structure may remain elastic or undamaged – a solution ideally suited for seismic upgrades of weak, brittle, heritage structures that preserves their heritage aspects and will also enable immediate use of the building after the earthquake. The first application in the world of seismic isolation for the upgrade of an existing building was the City & County Building in Salt Lake City, Utah, a large and architecturally impressive unreinforced masonry structure [1]. Seismic isolation has subsequently been used to retrofit and upgrade many heritage structures around the world, including buildings such as the New Zealand Parliament Buildings [2]. By comparison 'conventional' seismic upgrades dissipate energy in the structure by controlled damage (ductility), may have residual drift (not re-center), may or may not be repairable or useable after an earthquake, and are difficult to implement while also ensuring heritage preservation.

The seismic isolation solution requires the ability to accommodate very large lateral displacements at the isolation plane, necessary for the isolators to 'soften' the building response and dissipate the earthquake's energy.

The isolation scheme developed had the isolation plane at the upper level of the basement below the main floor and just above the windows, (not at the 'base' below the foundations); see Figure 2 for an exterior view of the building and the location of the isolation plane.

Figure 2. Basement, two storeys plus attic heritage classroom building; level of seismic isolation plane shown by dashed line.

A new concrete main floor slab, replacing the timber floor, was proposed to tie together the elements above the isolation plane and create a 'stiff' diaphragm above the isolators. New concrete columns, pilasters, basement exterior wall reinforcing and raft foundation were proposed to provide a 'stiff' structure below the isolation plane and a new vertical load path.

The estimated costs of the two conceptual upgrade schemes were essentially equal, for the cost estimate level of accuracy at that stage of the project. The seismic isolation scheme was selected for its superior post-earthquake performance and ability to provide a much higher level of heritage preservation.

MATERIAL TESTING

The absence of any original documentation showing the structural components of the building led to an extensive material testing and site investigation program, carried out after school hours, on weekends or during holidays. All testing and investigations were done at isolated locations, chosen based on the judgment of the structural engineers as to where representative construction characteristics were expected to be found.

Material testing included obtaining information on soil conditions, mortar shear capacity of brick walls on different floors and at different sides of the building, pull-out capacities of anchors proposed to be secured to both brick and stone, and hazardous materials such as asbestos and lead paint. The site investigation program helped to determine wall assemblies, floor assemblies, roof framing geometry and details, foundation depths, and specific details around windows.

Although extensive testing and investigation was done for this project, some unforeseen circumstances still occurred that needed the fast reaction of the design team in order to avoid delays during construction; two examples follow.

Five test pits were excavated to determine foundation depths and sizes. The new foundation system was designed based on the findings of these tests. However, during construction, it was found that in one corner of the building the existing foundations were considerably deeper than expected, leading to significant additional excavation and backfill.

Multiple 300 mm x 300 mm 'investigation pockets' were created through the drywall to determine the brick wall condition and composition throughout the building. Once construction started and drywall was removed, a series of wood nailers approximately 100 mm deep by 6mm thick were discovered at 1.5 m vertical spacing in all brick walls for the full height of the building. As this would affect the response and integrity of the walls for both in-plane and out-of-plane loading, all nailers were removed and infilled with mortar of a strength to match the original 120-year old mortar to create walls with the desired effective thickness and strength.

EARTHQUAKE GROUND MOTIONS

A total of 21 3-component earthquake accelerograms or time-history ground motion records in three different suites were selected and scaled to be consistent with the 2015 NBCC Uniform Hazard Spectrum (UHS), for site class C. The overall selection was based on a de-aggregation of the hazard for Vancouver, which provided mean magnitude and distance for the 2% in 50 year UHS. The database of 1148 records was that compiled by Daneshvar et al. [3]. The record selection and scaling followed the guidelines for time history selection and scaling, now included in Commentary J of the 2015 National Building Code of Canada (NBCC). The records were selected in three suites: five crustal records, five intraslab records, and 11 subduction records, in the approximate magnitude-distance range of interest, recorded on site class C or D; for scaling in the appropriate period band. This is summarized in Table 1.

Table 1. Magnitudes, distances (R_{rup}), and period bands for selection of three suites of records.

Source	Magnitude	R_{rup}	Period Bank
Crustal	M6.3 to M7.3	5 to 50 km	0.2 to 1.5 s
Intraslab	M6.5 to M7.5	50 to 120 km	0.2 to 1.5 s
Subduction	M8.2 to M9.2	80 to 250 km	1 to 4 s

After the records were selected and one component was scaled to match the horizontal-component UHS, a further scale factor was applied such that the geometric mean of the two horizontal components matched the UHS; a similar scaling factor for the corresponding vertical component was applied. Thus all three components were ultimately scaled by the same value, such that the original relationship between components was maintained. See Figure 3 for the geomean relative to the UHS.

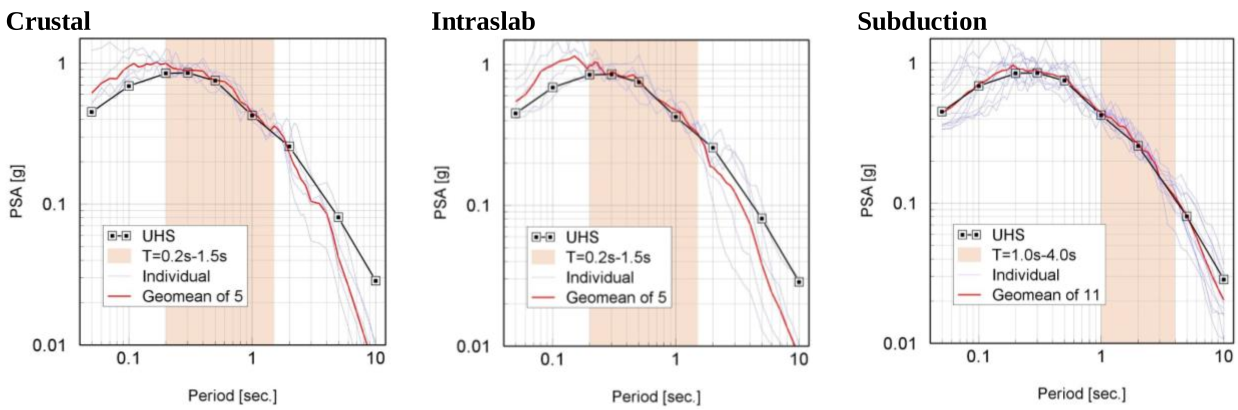


Figure 3. Horizontal component geometric mean (Geomean) relative to the UHS for the three different suites, scaled to be at or above the UHS in the applicable period range (note colour band shows period range for selection only; scaling for Crustal and Intraslab done for period range T=0.5 to 1.5 s; scaling for Subduction as shown for period range T=1 to 4 s).

ANALYSIS

The building response analyses were performed for the 21 earthquake ground motion records per three suites of records.

A full analysis, design and ultimately tendering, was carried out for both a Lead Rubber Bearing (LRB) combined with slider isolation system and a friction pendulum isolation system. The LRB/slider system was selected at the time of tender, and only this system is further discussed in this paper. Given the column configuration and the relatively light weight of the structure, it was determined that a combination of flat sliders and LRBs was required (not just LRBs) to meet the superstructure performance objectives set for the project.

The initial isolator properties were determined based on simple calculations and assumptions of the average load on the LRBs and sliders and the expected coefficient of friction for the sliders. The final design and configuration, including the number of LRBs versus sliders, was determined based on 3D non-linear analysis.

To account for variability in the isolators and sliders, the lower and upper bound property modification factor methodology of AASHTO [4] was used, to account for the effects of ageing, temperature, rate of loading, cyclic loading and manufacturing variability. The resulting upper bound LRB second slope stiffness, Kd, was 25% greater than the nominal value, and the upper bound characteristic strength, Qd, was 50 percent greater than the nominal value. The lower bound values for both strength and stiffness were 15 percent lower than the nominal values.

The non-linear time history analysis of the structure and the isolation system was conducted using the Fast Non-linear Analysis (FNA) algorithm of SAP2000 [5]. The suitability of the isolation system was judged based on the response of the system to each of the three suites of motions. For each suite, the analyses considered both 'rigid' and flexible foundation conditions and the assumed upper and lower bound isolator properties, to account for the variability in the properties; thus four unique 3D computer models were analysed for each suite of records. The period of the isolated building varied from approximately 2.5 seconds to 3.4 seconds for the four models noted; for comparison, the period of the existing 'fixed base' building was determined to be approximately 0.3 seconds. For each suite, the mean and mean-plus-one standard deviation was calculated for the inter storey drift, base shear, accelerations at selected critical points and the isolation system deformation (per the intent of NBCC 2015).

As is the case with all isolated structures, the correct combination of axial load and horizontal displacement values is important to ensure stability of the bearings under extreme loading conditions. To determine the time-coincident maximum displacement and axial load for the bearings, the displacement time histories in the two horizontal directions were combined via SRSS ("Square Root of Sum of Squares"). With this value, the time-coincident axial load was then determined to define the maximum isolator displacement and axial force combination for design and prototype testing of the isolators.

The LRB properties (Kd and Qd) were updated based on the bearing properties obtained from the prototype tests. The slider properties (coefficients of friction) were also updated on the basis of dynamic test results submitted by the bearing manufacturer. The refined properties were within the tolerance limits specified in the tender documents; as such the building response was confirmed to satisfy the design performance criteria set for the building.

All LRB isolators were 'production' tested and the as-tested properties were used in re-analysis to assess the 'as-built' response of the isolated building. A second set of LRB properties was also considered in the re-analysis based on the expected long-term properties of the LRBs. The backbone of the 'As-Tested' and 'Aged Properties' are plotted in Figure 4. The base shear limit (for the superstructure above the isolation plane) of 15% of the weight of the superstructure as well as the equivalent lateral load due to 1/50 year wind event are also indicated for reference in Figure 4. The graph is plotted up to a displacement of just over 200 mm, the maximum value obtained from the mean-plus-one standard deviation output from all of the non-linear time-history analyses.

An LRB test cycle was conducted by imposing a maximum displacement of 90 mm in each direction. The energy dissipated per each complete cycle was about 11 kN.m for the as-tested LRB and about 8.1 kN.m was used for the expected long-term LRB backbone, as shown in Figure 5.

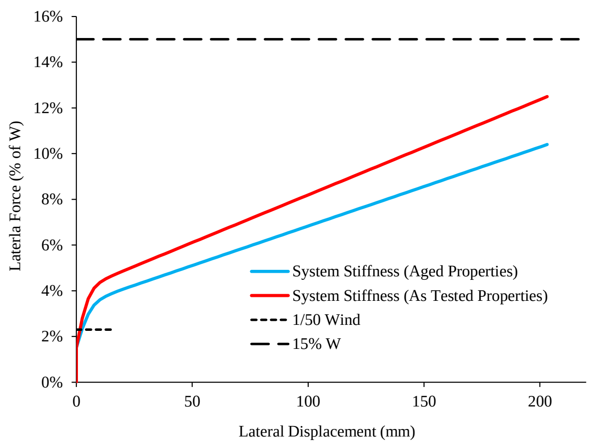


Figure 4. Force displacement properties of LRBs – As-Tested and Aged Properties.

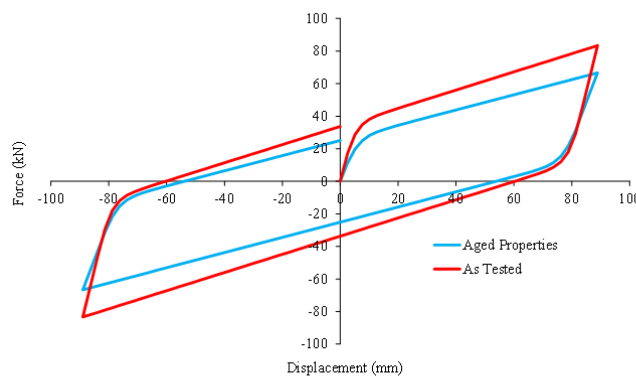


Figure 5. LRB test cycle to evaluate energy dissipation.

DESIGN

The design of the isolators involved numerous iterations of non-linear analysis to finalize the 12 LRB/18 slider isolator mix for the specific properties and weight of the building; the design ensures elastic isolator movement (millimetres) for design wind loading, but the necessary movement at the isolation plane to dissipate the energy of the design earthquake. See Figure 6 (following page) for a plan layout of the isolator locations.

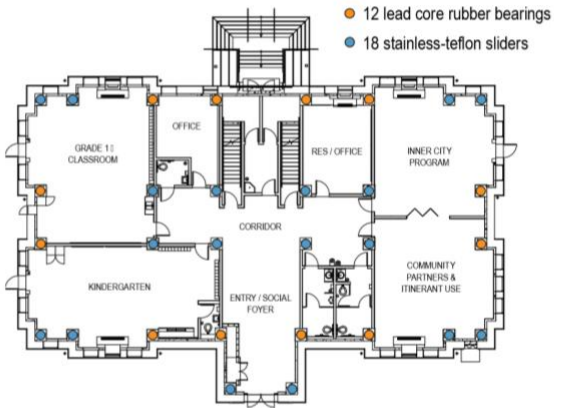


Figure 6. Basement plan showing locations of bearings and sliders.

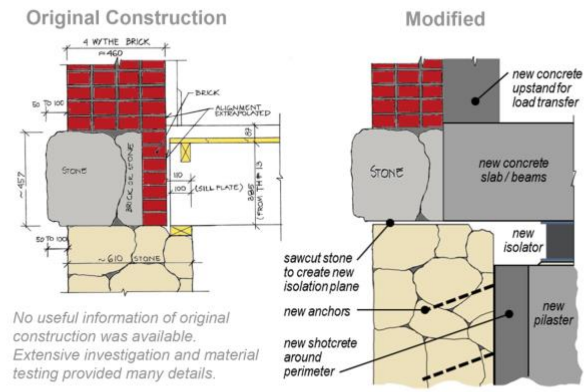


Figure 7. Comparison of Exterior Wall before and after isolation work completed.

The design included the following key aspects: demolition of entire basement slab and replacement with a new 'rigid' foundation for 8 new columns, 22 new pilasters, and new perimeter shotcrete walls – a very stiff below-isolation plane structure is critical to ensure the lateral deformation is focussed in the new isolators; demolition full height of central three-storey load bearing brick wall (while shoring upper floor and attic to stringent deformation tolerances of less than 4 mm) – essential for new architectural layouts and circulation; demolition of basement portions of four other load bearing brick walls (while shoring upper two storeys, again to stringent deformation tolerances); demolition of entire main elevated timber floor – for new concrete floor to act as a 'rigid' diaphragm above the new isolators and stiff enough to transfer all vertical load to the isolators; and new steel columns/timber beams in the upper floors as part of the new vertical load path.

The design also included new upstand concrete beams at the perimeter of the main floor which were critical to the success of the project – to ensure load transfer from the exterior brick walls into the new concrete slab, then into the isolators, for the permanent condition when the walls were saw-cut. See Figure 7 above for an illustration of the original exterior wall compared to that after the isolation system was complete. A 'triple' redundant design was achieved to ensure load transfer with less than 2 mm movement of the original structure above: a mechanical wedge design; and two sets of epoxy anchors (one to stone, one to brick) provided the redundancy.

Another key design feature was saw-cutting the 610 mm exterior stone wall to complete the isolation plane and ensure no load was carried by the exterior basement walls but rather was transferred fully to the isolators. This also required details to ensure that no part of the basement stone walls impeded the predicted 250 mm of lateral movement at the isolators. See Figure 8 (following page) for a photo of saw-cutting and completed joint.

Finally, all architectural components and mechanical and electrical services crossing the isolation plane were custom designed to accommodate 250 mm of lateral movement. The new basement partition walls had a unique design; the bottom portion was 'cantilevered' from the foundation below the isolation plane, and the portion above the plane was suspended from the underside of the floor slab above. See Figure 9 (following page) for a photo of a portion of the basement wall and flexible mechanical/electrical services at that location. Custom two-hour, fire-rated enclosures were designed for the isolators; the enclosure at its midsection will also accommodate 250 mm of movement.

JACKING AND LOAD TRANSFER PROCESS

The jacking created a separation plane below the new concrete slab in order to decouple the upper portion of the building from the lower portion. Hydraulic jacks were located between the top of the concrete columns and the bottom of each isolator with shoring in place until the jacking was complete; see Figure 10a and Figure 10b (following page). The first use in Canada of 'flat jacks' or 'plate jacks'–approximately 450 mm in diameter and 25 mm thick–were expanded only 3.3 mm to transfer the building load onto the new isolators. A system was developed to first pressurize all 30 flat jacks using a 'water like' fluid, then return and re-balance (fine tune) the loads and deformations at each location, and finally transfuse high strength epoxy into the jacks making them a permanent part of the vertical load carrying system. This involved 9 set up locations, 22 increments of loading, and 22 surveys and visual inspections to ensure specific load and deflection criteria were met and no damage occurred to the exterior heritage façade. A summary of final loads and deflections after balancing and epoxy transfusion is shown in Figure 10c (following page); the maximum vertical movement to achieve load transfer was 3.3 mm, and the maximum jacking load was 921 kN.

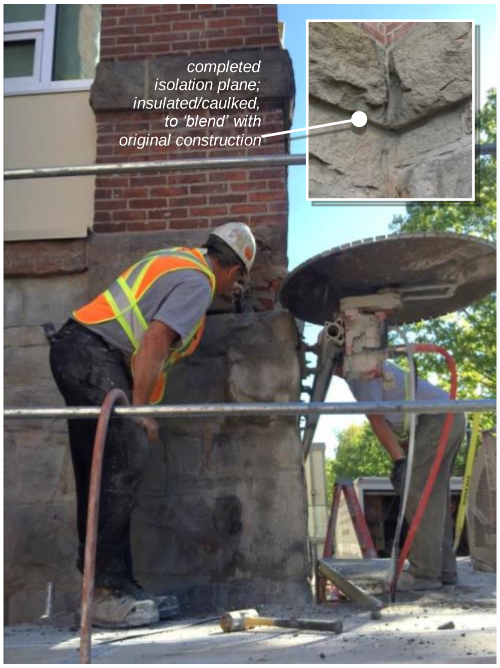


Figure 8. Sawcutting equipment with inset showing final joint at the isolation plane

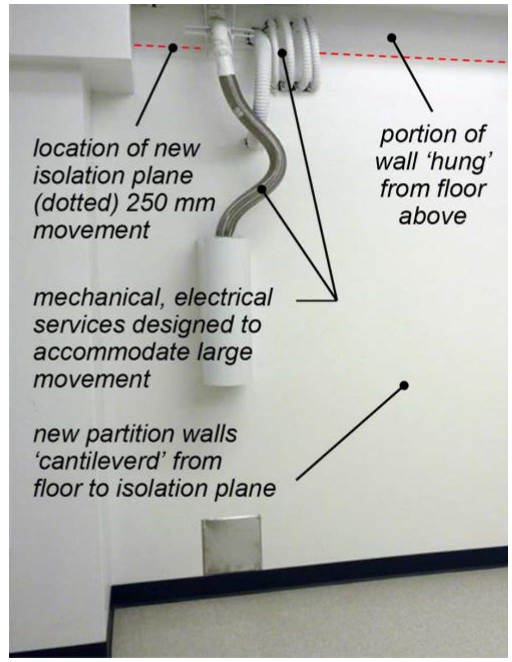


Figure 9. Illustration of basement wall and details to accommodate 250 mm movement at isolation plane.

Figure 10. a) View of slider during jacking (left, top) b) Slider location atop column, shoring in place (left, bottom) c) Force-Deflection summary after load transfer complete.

CONCLUSIONS

Non-linear time-history analyses for the design of the isolation system considered a total of 21 different earthquake ground motion records grouped in three suites of earthquake types: subduction, crustal, and intraslab. To account for variations in concrete and soil properties, and variations in properties of the isolators, four different 3D models of the building were analysed, with non-linear time history analyses performed for each.

Subsequent to every isolator being tested per a very specific testing protocol, all analyses were completely repeated using actual tested properties of the isolators used in the construction. The design of the isolators involved numerous iterations of the non-linear analyses to ultimately finalize the 12 LRB/18 slider isolator mix for what is a relatively ‘light’ building.

The design included: demolition of the entire basement slab and replacement with a new ‘rigid’ foundation for 8 new columns, 22 new pilasters, and new perimeter shotcrete walls; demolition full-height of the central three-storey load bearing brick wall; demolition of the main elevated timber floor for a new concrete floor; new upstand concrete beams to ensure load transfer from the exterior brick walls into the new concrete slab; a Canada-first use of ‘flat jacks’ to transfer all of the building load onto the new isolators; saw-cutting the exterior stone wall to complete the isolation plane; architectural components and mechanical and electrical services crossing the isolation plane that can accommodate the predicted 250 mm of lateral movement. Ongoing liaison with the contractor and owner was essential to effectively implement the design and the modifications and adjustments during construction.

The base isolation upgrade will enable this building to be fully functional after the design earthquake (pending utilities entering/leaving the property being functional), and provides heritage preservation of this 120-year old neighbourhood gem.

In 2017, this project was recognized with the Association of Engineering Companies of BC (ACEC-BC) Award of Excellence - Buildings Category and the ACEC-BC Lieutenant Governor's Award (top project overall).

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