The case for base isolation in low to moderate seismic zones

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ABSTRACT

Around the world, base isolation is widely used in high seismic zones to protect new and existing structures from earthquake ground motions, and is very effective in reducing seismic demands for low-rise, stiff structures. Heritage buildings tend to be low-rise masonry-based structures; by their nature, these structures are stiff and brittle. It is widely understood that this type of construction is particularly at risk under earthquake loading, and that many heritage buildings need to be upgraded for seismic loads even in areas of moderate to low seismic hazard such as eastern Canada. Conventional seismic upgrades can result in significant structural interventions within the building to add strength to the structure and rationalize load paths. These upgrades are often in conflict with the goal of preserving heritage finishes within the building and limiting deformations to the very low level required for heritage preservation of the exterior masonry can be difficult. To date, base isolation has not been extensively used in Canada; however, design requirements for base isolation are now included in the 2015 National Building Code of Canada. This paper provides an overview of base isolation as applied to heritage buildings, and looks at the effectiveness of using base isolation on heritage buildings in regions of low and moderate seismicity by comparing the relative costs of conventional and base isolation seismic upgrades for heritage buildings in Ottawa. It is concluded that base isolation as a seismic upgrading solution for heritage buildings in low and moderate seismic zones is not only a viable option, but in fact can be more effective and have greater benefits than in high seismic zones.

Keywords: seismic, isolation, upgrading, heritage, masonry

INTRODUCTION

Base isolation of new buildings to provide protection from earthquake ground motions has been employed worldwide for many years. It has been shown to be very effective at reducing seismic demands for low rise, stiff structures. Many existing buildings have also been retrofitted with base isolation as part of a seismic upgrade. Base isolation has been found to be a particularly effective solution for improving the expected seismic performance of heritage masonry buildings. Two such examples are the Salt Lake City and County Building and the San Francisco City Hall, shown in Figure 1 below. However, to date, base isolation has only been commonly applied in regions of high seismicity.

This paper discusses the applicability of base isolation to the seismic upgrade of buildings located in low to moderate seismic zones. The advantages of a seismic upgrade that incorporates base isolation for heritage masonry buildings located in low to moderate seismic zone are reviewed. The potential seismic force reduction and anticipated lateral movement at the isolation plane are also commented on. Finally, the findings of a comparative cost study of a conventional seismic upgrade versus a base isolation seismic upgrade for two buildings located in a moderate seismic zone (Ottawa, Canada) are presented.

(a) Salt Lake City and County Building [1]

(b) San Francisco City Hall [2]

Figure 1. Examples of base isolated heritage masonry buildings

BASE ISOLATION OF HERITAGE MASONRY BUILDINGS

Heritage masonry buildings are considered valuable community assets both for their functional value as infrastructure and for their symbolic and iconic status. Unfortunately, due to their age and method of construction, heritage masonry buildings are often vulnerable to damage during a seismic event. Many heritage masonry buildings are load bearing masonry structures, i.e. they use masonry walls to support the vertical weight of their floors. This type of construction tends to have a large quantity of walls in comparison to modern frame construction buildings. Heritage masonry structures are also commonly low-rise structures (relative to their overall plan dimensions). The combination of these two attributes results in very laterally stiff structures. In addition, heritage masonry buildings tend to be very heavy due to the mass of their structural system. Consequently, heritage masonry buildings attract a high level of lateral force during seismic shaking. Unfortunately, although they are laterally stiff, their unreinforced masonry construction provides a relatively low lateral load resistance. Structural failures under lateral loading can occur in a brittle manner and may be catastrophic in nature. This type of failure presents a substantial risk to occupant life safety and can also result in the complete loss of an irreplaceable heritage asset. Consequently, it makes sense to invest in the protection of a heritage masonry building asset with seismic upgrading even in areas of moderate to low seismic hazard.

Conventional methods of seismic upgrading involve the insertion of additional structure to increase the lateral load resistance of a building eg. new concrete walls or steel braces. Typically, ductile behaviour of the strengthened system is relied upon to absorb seismic energy. In properly detailed designs, this can be quite effective at resisting seismic loads. However, it still results in damage (albeit controlled damage) and permanent deformation to the upgraded building.

When applied to heritage masonry buildings, conventional seismic upgrading techniques present several engineering challenges. Firstly, due to the inherent stiffness of these structures caused by their large number of walls, any new bracing elements added to these structures to increase their lateral strength need to be correspondingly stiff to limit deformations to the very low level required for preservation of heritage masonry. If the new strengthening elements are too laterally flexible, then they cannot effectively protect the original heritage masonry from incurring significant damage during seismic shaking. As a brittle material, unreinforced masonry has very limited ability to achieve ductile behaviour. Consequently, the added structural strengthening elements need to be large, numerous and laterally stiff. Insertion of these elements into a heritage masonry building often constitutes a very large intervention and results in significant disruption to heritage finishes. Secondly, it can be difficult to hide the additional strengthening elements or to find sufficient acceptable locations to place them. Figure 2 below provides examples of conventional seismic upgrading using large structural steel cross bracing.

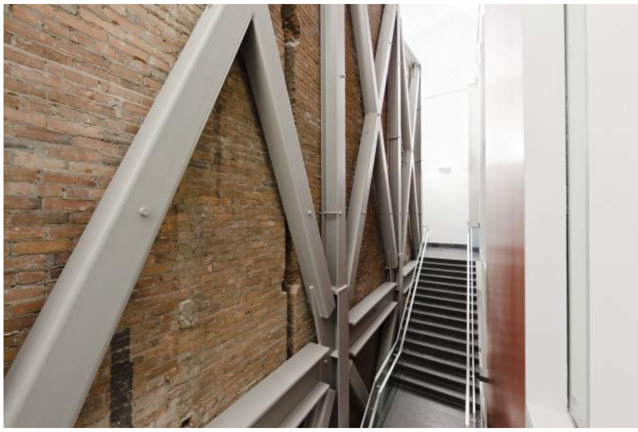

Figure 2. Structural steel seismic bracing – Canadian Museum of Nature, Ottawa. [3]

An alternate approach to a conventional seismic upgrade is one that incorporates base isolation. With this approach laterally flexible isolator units are used to separate a building from the ground. Many different types of isolators have been developed. These include lead rubber bearings, high damping rubber bearings, flat sliding bearings and friction pendulum systems. Figure 3 shows an example of an isolator installation. Regardless of the type of isolator, all isolators serve to minimize the seismic energy that can be transferred from the ground to the building's superstructure by lengthening its natural period of vibration. As illustrated in Figure 4 below, rather than attempting to increase the lateral load capacity of building as is the case with a conventional seismic upgrade, a base isolation seismic upgrade approach aims to reduce the seismic demand instead.

Figure 3. Isolator below the Utah State Capitol Building [4]

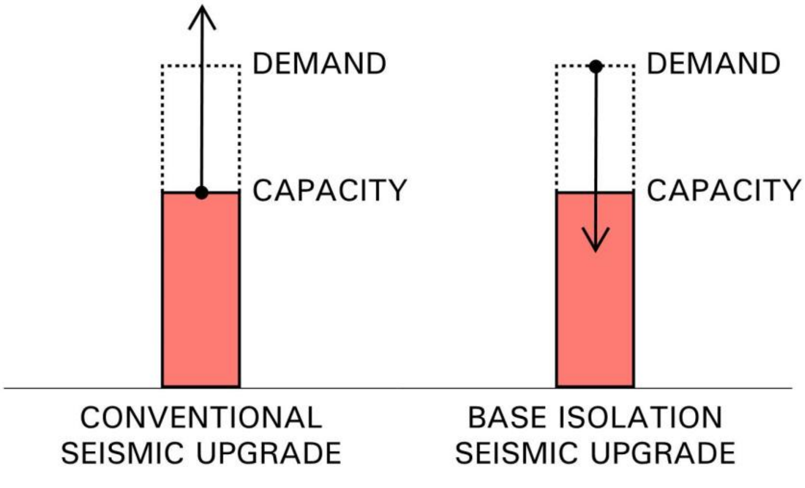

Figure 4. Conceptual difference between a conventional vs. base isolation seismic upgrade approach

The key requirements of a base isolation seismic upgrade scheme are illustrated in Figure 5 below. They include the following:

1) An isolation plane below which the isolators are located. The isolation plane can be located at the base of a structure or at a suspended level such as at the underside of the ground floor slab for buildings with a basement.

2) A moat/movement gap at the isolation plane to permit unrestrained lateral displacement of the isolators.

3) A strong floor diaphragm immediately above the isolation plane to tie the superstructure together and prevent differential movements from occurring.

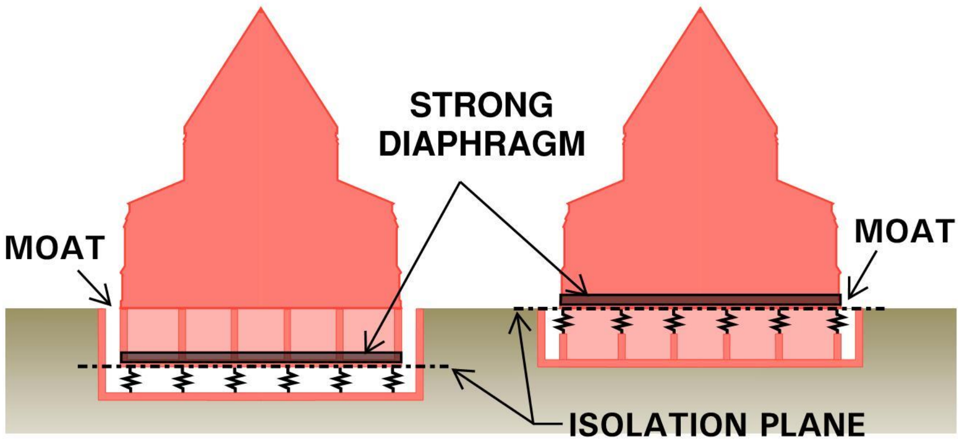

Figure 5. Key requirements of a base isolation scheme

Buildings that are suitable to be retrofitted with a base isolation seismic upgrade are buildings that have an existing (but inadequate) structural system for resisting lateral loads, are heavy and are laterally stiff. Typically, heritage load bearing masonry buildings satisfy all these criteria. Base isolation is an especially advantageous seismic upgrade solution for these buildings as the bulk of the structural work is concentrated in the basement or at the foundation level. Intervention into the more sensitive heritage areas can be significantly reduced or eliminated. A further advantage of base isolation for heritage masonry buildings over a conventional seismic upgrade is the enhanced protection that it provides for heritage finishes. Since base isolation limits the seismic energy entering the overall building, it effectively protects not just the structure of the building but also its heritage fabric, e.g. its floor and wall finishes, ceilings, and ornamentation. It should be noted that these reasons for selecting base isolation as the seismic upgrade approach for a heritage masonry building apply regardless of the seismic hazard level.

SUPERSTRUCTURE SEISMIC FORCE REDUCTION

As noted above, base isolation minimizes the seismic energy that can be transferred from the ground to a building's superstructure by lengthening its natural period of vibration. The low lateral stiffness of the isolators shifts the natural period of the superstructure beyond the predominant period of typical earthquakes [5]. This behaviour is illustrated in Figure 6. Example acceleration response spectrums for a high seismic zone (Vancouver) and a moderate seismic zone (Ottawa) are shown. A fundamental period shift due to base isolation from 0.2 seconds to 2.5 seconds is indicated on the spectrums. These are the approximate initial period and base isolated period that might be expected for a stiff heritage masonry building. For this scenario, the superstructure force reduction achieved due to period shift on the high seismic spectrum is approximately 70%. By comparison, the superstructure force reduction achieved on the moderate seismic spectrum is approximately 90%. The absolute force reduction is lower; however, the relative reduction is higher for the moderate seismic spectrum. The increased benefit is caused by the different shapes of the two example spectrums. The moderate seismic zone spectrum reduces faster with increasing fundamental periods than the higher seismic zone spectrum. This is a common characteristic of low to moderate seismic zone acceleration spectrums. It may be observed that base isolation is as effective, if not more so, at reducing superstructure seismic design forces in a low to moderate seismic zone as in a high seismic zone.

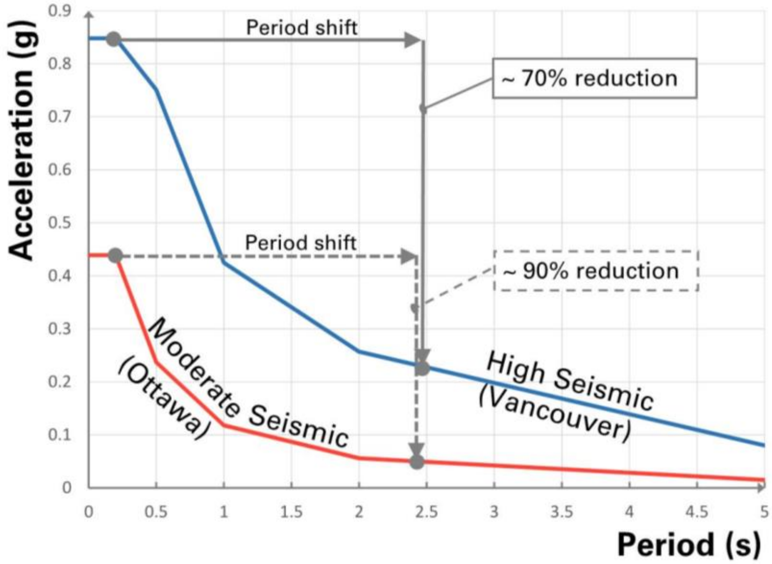

Figure 6. Seismic force reduction due to fundamental period shift caused by base isolation

SEISMIC MOVEMENT GAP

One of the key requirements of a base isolation scheme is to allow the isolators unrestrained freedom to displace laterally. Without this freedom to displace, the period shift and superstructure force reduction cannot be achieved. Since the isolation plane of a base isolated building is commonly located below grade, this requirement results in the need for a seismic movement gap or 'moat' around a base isolated building (refer Figure 5). Sufficient space between a base isolated building's superstructure and any adjacent buildings is also required. Provision of adequate separation to neighbouring structures can be one of the biggest challenges with any seismic upgrading project. This is especially true for a base isolation retrofit since the required movement gap will be significantly larger than what would be required for a conventional seismic upgrade. Furthermore, all utilities, services, elevators and stairs crossing the isolation plane must be able to accommodate the anticipated lateral displacement of the isolators. In a high seismic zone, the anticipated lateral movement of the isolators might be in the range of 350-500mm. In a low to moderate seismic zone, the anticipated lateral movement would be much less, potentially in the 100-200mm range. Consequently, the detailing for a seismic moat, expansion gaps and movement joints in utilities, services, elevators and stairs that cross the isolation plane is likely to be more easily achieved when implementing a base isolation seismic upgrade scheme in a moderate seismic zone than in a high seismic zone.

COST-EFFECTIVENESS OF BASE ISOLATION

As mentioned previously, base isolation can significantly reduce or eliminate the quantity of work required to seismically upgrade the superstructure of a building. This may result in a reduced overall seismic upgrade cost if the reduction in superstructure work is sufficient to offset the added work required at the basement/foundations for implementation of base isolators. The most cost-effective scenario occurs when little or no superstructure work is required, i.e. the seismic demands on a building's superstructure are lowered such that the modified seismic demand falls below the existing seismic capacity threshold of the building. This is illustrated in Figure 7. This optimal scenario is more likely to occur for buildings located in low to moderate seismic zones than for buildings located in high seismic zones, since their overall seismic hazard is less. Despite this, base isolation may still be the preferred seismic upgrade option in a high seismic zone for a heritage masonry building, since with a high seismic demand and a low seismic load resistance, there may be little other avenue for achieving satisfactory seismic performance.

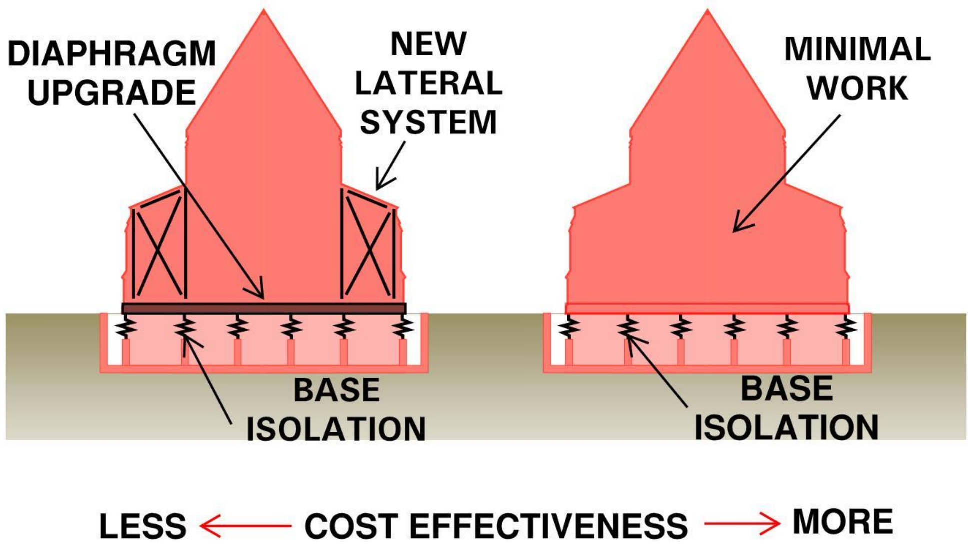

Figure 7. Cost effectiveness of a seismic upgrade incorporating base isolation

This observation has been validated by two recent studies, [6], [7], conducted by the authors of this paper on two heritage masonry buildings located in Ottawa, Canada. Ottawa is considered a moderate seismic zone, with a short period spectral acceleration for Site Class C of Sa(0.2)=0.439 and a one-second spectral acceleration of Sa(1.0)= 0.118 [8]. The studies were performed on the Canadian Parliament Centre Block building and the West Memorial building (see Figure 8 below) at the request of the buildings' owner, Public Services and Procurement Canada (PSPC). Each study included the development and costing of a preliminary conventional seismic upgrade scheme and a base isolation scheme. The studies concluded that for these specific buildings, the estimated cost of a base isolation seismic upgrade was very similar, if not less expensive, than a conventional seismic upgrade. The reduction in superstructure work was found to be adequate to offset the cost of the base isolation implementation. Each study recommended that base isolation be considered as a viable option for a future seismic upgrade. It was also noted that despite the similar cost, the base isolation seismic upgrade schemes offered the opportunity to achieve a significantly higher standard of seismic performance, post-earthquake functionality and heritage preservation than a conventional seismic upgrade.

Canadian Parliament Centre Block Building, Ottawa [9]

West Memorial Building, Ottawa [10]

Figure 8. Examples of heritage masonry buildings

CONCLUSIONS

The following conclusions are drawn regarding the application of base isolation in low to moderate seismic zones:

- For heritage masonry buildings, a base isolation seismic upgrade scheme creates the opportunity to concentrate seismic upgrade work in a non-heritage basement/foundation area, with less work undertaken in the upper heritage portion. This is as true for heritage buildings located in low to moderate seismic zones as it is for heritage buildings located in high seismic zones.
- For heritage masonry buildings, base isolation provides effective protection to not just the building's structure, but also its heritage finishes. This can be difficult to achieve with a conventional seismic upgrade, regardless of seismic hazard.
- The relative superstructure force reduction that can be achieved with a base isolation seismic scheme is potentially greater for a building located in a low to moderate seismic zone than for a building located in a high seismic zone.
- The anticipated lateral displacements of isolators under seismic loading is much less for buildings located in a low to moderate seismic zone that for buildings located in a high seismic zone. Consequently, detailing of a seismic movement moat and structural separation to adjacent structures will be more easily achieved for base isolated buildings located in a low to moderate seismic zone than for base isolated buildings located in a high seismic zone.
- Detailing of movement joints in utilities, services, elevators and stairs that cross the isolation plane will also be much more easily achieved when implementing a base isolation seismic upgrade scheme in a low to moderate seismic zone than in a high seismic zone.
- Depending on the specific characteristics of a buildings, the quantity of seismic upgrade work avoided with the use of base isolation is potentially larger for heritage masonry buildings located in low to moderate seismic zones than for buildings located in high seismic zones. Correspondingly, the cost-effectiveness of base isolation as an upgrade scheme may be potentially greater for heritage buildings in low to moderate seismic zones.
- For the reasons listed above, base isolation should be explored as an option when performing preliminary seismic upgrade studies for heritage masonry structures in low to moderate seismic zones.

REFERENCES

[1] *"Salt Lake City and County Building"* by "Daderot". Wikimedia Commons (Public domain).

[2] "*San Francisco City Hall*" by "Sanfranman59" Licensed under a Creative Commons Attribution-ShareAlike 3.0 Unported license. https://commons.wikimedia.org/wiki/File:San_Francisco_City_Hall_2.jpg

[3] Photo credit: Eric Fruhauf, PKG Architects

[4] "*The seismic dampening widgets (Base Isolators) under the Utah State Capital building*" by Mike Renlund. Licensed under a Creative Commons Attribution 2.0 Generic license. https://commons.wikimedia.org/wiki/File:Base_isolators_under_the_Utah_State_Capitol.jpg

[5] Christopoulos, C., and Filiatrault, A. (2006). "*Principles of Passive Supplemental Damping and Seismic Isolation".* IUSS Press, Pavia Italy.

[6] Halsall Associates (2015). "*High Level Seismic Upgrade Cost Estimate for Centre Block, Parliament Hill*". Report 20150336 prepared for Public Works and Government Services Canada.

[7] Halsall Associates (2015). "*Final Report West Memorial Building Rehabilitation Seismic and Loading Assessment for 344 Wellington Street, Ottawa, Ontario*". Report R.061599.307 prepared for Public Works and Government Services Canada.

[8] National Research Council of Canada (2015). "*2015 National Building Code of Canada*." National Research Council of Canada.

[9] *"Centre Block – Parliament Hill*" by "Saffron Blaze" Licensed under a Creative Commons Attribution-ShareAlike 3.0 Unported license. https://commons.wikimedia.org/wiki/File:Centre_Block_-_Parliament_Hill.jpg

[10] *"West Memorial Building and East Memorial Building"* by "_muckraker_*"* Licensed under a Creative Commons Attribution-Share Alike 2.0 Generic license. https://commons.wikimedia.org/wiki/File:West_Memorial_Building_and_East_Memorial_Building.jpg