# Retrofitting Heritage Buildings for Energy and Seismic Upgrades

by
Mohsen Kobraei
Bachelor of Science, Islamic Azad University, Iran, 2007
Master of Engineering Science, University of Malaya, Malaysia, 2012

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of
MASTER OF APPLIED SCIENCE
in the Department of Civil Engineering

# Supervisory Committee

Retrofitting Heritage Buildings for Energy and Seismic Upgrades

by
Mohsen Kobraei
Bachelor of Science, Islamic Azad University, Iran, 2007
Master of Engineering Science, University of Malaya, Malaysia, 2012

**Supervisory Committee**

Dr. Phalguni Mukhopadhyaya, Department of Civil Engineering
**Co-Supervisor**

Dr. Caterina Valeo, Department of Mechanical Engineering
**Co-Supervisor**

Dr. Lina Zhou, Department of Civil Engineering
**Departmental Member**

# Abstract

The application of retrofit options to existing heritage buildings has become one of the most interesting topics in construction. In Victoria, BC, Canada, only 4% of commercial or institutional heritage buildings have been upgraded to current building codes in the last 10 years. Remaining 96% buildings exist with poor energy performance characteristics and a risk to occupant safety in the event of a damaging earthquake. This study investigates the importance and benefits of simultaneous energy and seismic retrofitting of existing heritage buildings. It presents a case study for a building with identifiable heritage value, located in Victoria, BC, Canada, and analyzes five feasible options in terms of energy retrofitting and presents a solution for both seismic and energy upgrading. To this aim, the energy retrofit options are compared based on the amount of saved energy, annual heating demand and estimated costs. The seismic solution is designed based on the weakness and needs of the building, and cost-effectiveness. Finally, the best solution is selected for a building that dates back to the beginning of the 20th century. This study shows that the integration of energy and seismic retrofitting of heritage buildings provides economic benefits to owners while improving energy savings and building safety.

# Table of Contents

This thesis work is dedicated to my wife, Mahta, who has been a constant source of support and encouragement during the challenges of graduate school and life. I am truly thankful for having you in my life.

This work is also dedicated to my parents, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

# Acknowledgements

I would like to express my deepest appreciation to Dr. Phalguni Mukhopadhyaya for his patience, motivation, enthusiasm and immense knowledge. His guidance helped me all the time of my research at the University of Victoria. I could not have imagined a better advisor for my MASc. study.

It is my pleasure to express my appreciation to Dr. Caterina Valeo, who has been a great source of support, inspiration, and constants encouragement.

I would like to thank my friends and colleagues at Waymark Architecture for providing me an opportunity to join their team as research and development lead and gave access to the research facilities and knowledge base. Also, I must gratefully mention that this research was supported and funded by a grant from MITACS and Waymark Architecture.

I would like to extend my sincere thanks to Mr. Murray Forsyth, for his time and excellent guidance for technical writing.

Finally, heartfelt thanks extended to my beloved family for their love, support and encouragement through the process of researching and writing this thesis. Thank you.

# List of Figures

# List of Tables

# Chapter 1

# Introduction

## 1.1. Background

Today, seismic retrofitting of existing buildings, especially old and heritage buildings, has become one of the most important and interesting topics. Buildings that may have met the old seismic standards until several years ago do not meet the current requirements. Buildings require retrofitting due to many reasons including i) damages caused by natural hazards such as earthquakes, ii) lack of seismic resistance iii) or because of biological decay and chemical corrosion. Along with all these, add poor energy performance of building envelopes which is directly related to the age of the structure. Prior to 1997, there were not energy efficiency codes in Canada, and buildings had not been required to meet energy-saving principles. This study presents the best solutions for energy retrofitting based on cost-effectiveness and energy efficiency. The seismic solution is applied based on a possible option that reinforces parts of the building that cannot be replaced with a new structure.

## 1.2. Reasons of Interaction of Energy and Seismic Retrofitting

In Canada, almost 57% of commercial and industrial buildings were built prior to 1980 [1]. Among them, 406 commercial or institutional heritage buildings exist in Victoria, BC [2]. Despite the fact that Victoria has a one-in-three probability of experiencing a damaging earthquake in the next 50 years [3], only 4% of these buildings have been upgraded to current building codes in the last 10 years [4].

On the other hand, buildings are responsible for the majority of emissions in urban centers. Hence, one B.C. provincial goal is a reduction by 40% of carbon emissions by 2030 using the 2007 energy code as baseline [4]. Since the first Canadian energy standard introduced in 1997, it can be said that more than 50% of existing buildings do not meet energy requirements [5]. Model National Energy Code for Buildings (MNECB) in 1997 was Canada's first national standard for building energy performance. This code influenced buildings for more than 15 years. It was revised in 2011 and renamed the National Energy Code for Buildings (NECB 2011). the National Energy Code for Buildings (NECB) including an average of 25 percent performance improvement over its predecessor. The next edition was updated and released on December 18, 2015. In view of seismic resistance, old buildings are more vulnerable during natural hazards [6]. It is reported old buildings are more at risk of economic losses and serious injuries of occupants [6]. Therefore, the older buildings, the more need for energy and seismic retrofit.

Data show the replacement of old buildings with new constructions, which meets all the seismic and energy standards, is not a viable alternative based on two main reasons: (i) construction costs [6] and (ii) the amount of pollutants emitted to the environment during the construction [7]. Although retrofitting existing buildings that fulfill seismic and energy requirements is much more complex than building new buildings [8], life-cycle assessment (LCA) reveals that the total greenhouse gas (GHG) emissions of a new building in construction phase is much higher than that of emanating from retrofitting of an existing building [7]. Hence, retrofitting could be an eco-friendly option in comparison with new constructions. Therefore, in view of importance and benefits, it is very crucial for decision-makers to upgrade existing buildings in accordance with seismic and energy requirements simultaneously instead of opting for new constructions. It should be noted that very few studies and limited research have been accomplished to date that show the potential synergies of seismic and energy retrofitting.

# Chapter 2
# Literature Review

## 2.1. Energy Retrofitting

As indicated before, energy retrofit of existing buildings is one of the fundamental solutions in reducing GHG emissions and energy consumption. Many measures and criteria towards energy efficiency and decreasing total energy consumption have been recommended.

There are four recommended retrofit criteria to reduce the environmental impacts of existing buildings. These criteria are i) increased R-value of building envelope; ii) use energy-efficient heating, cooling and lighting systems; iii) apply passive solar energy; and iv) repair of damaged parts of the building during service life [9]. It is obvious these criteria are related to the geographic and climatic conditions [10], [11]. The following paragraphs show some case studies that have used the mentioned criteria for energy retrofitting depending on the type of building.

### 2.1.1. Selected Case Studies

In a study, the effect of lightweight timber-glass on energy consumption of three existing buildings built in the 1950s and 1960s located in Maribor, Slovenia was examined [12]. Base on the results, 46% of the total energy demand was saved by extending attics of the buildings and using wood frame windows. Another study reported the saved amount energy to 58% by using (i) thermal resistance insulation materials; (ii) energy-efficient boilers; and (iii) a grid-connected photovoltaic plant [10].

Table 2.1 shows the five used phases of building retrofitting process. It is noted, however, the success in retrofitting depends on more items including (i) human factors; (ii) technology; (iii) client resources and expectations; and (iv) building-specific information [11]. Insulating ceiling and external walls, sealing and energy-efficient ventilation systems are the most cost-effective options [11].

Table 2.1, Key phases in a sustainable building retrofit program [11]

| Phase I | Phase II | Phase III | Phase IV | Phase V |
|---|---|---|---|---|
| Project setup and pre-retrofit survey | Energy auditing and performance assessment | Identification of retrofit options | Site implementation and commissioning | Validation and verification |
| - Define scope of work<br>- Set project targets<br>- determine available resources<br>- Pre-retrofit survey | - Energy auditing<br>- select key performance indicators<br>- Building performance assessment & diagnostics | - Energy saving estimation<br>- Economic analysis<br>- Risk assessment<br>_ Prioritize retrofit options | - Site implementation<br>- test and commissioning (T&C) | - Post measurement and verification (M&V)<br>- Post occupancy survey |

In a historical building to have the ideal room temperature in different weather conditions, four energy retrofit options were addressed. These options are (i) improved sealing; (ii) insulated external walls; (iii) use a gas heater instead of the old boiler; and (iv) upgrad doors and windows [13]. Each of these options reduced annual energy consumption—up to 22%— with the payback period of 11 years [13].

A two-story building built in the late 1960s in Vancouver, BC, Canada, was retrofitted with high-performance insulation materials and an energy-efficient heating and cooling system. The outputs show a 45% reduction in the total annual energy consumption with a payback of 7.7 years. This reduction saved almost 70 tons of CO2-eq per year. As a hypothetical scenario, the amount of saved energy for the same building in Montreal, QC, Canada, is 39% [14].

In a building located in Barcelona, Spain, Extruded Polystyrene (XPS) foam on the exterior side of external walls was the only energy retrofit option. Data have been collected during winter 2009 and 2010 and from four units in the building. It is mentioned the layout of units has an impact on the energy consumption of the building [15]. For example, rooms with an exterior façade showed less energy consumption [15].

## 2.1.2. British Colombia (BC) and Canada Energy Standards

Technically, the main purposes of building energy standards are to ensure thermal comfort, air quality, building envelope, electrical lighting, mechanical heating, cooling & ventilation systems, and hot water systems. Before Canada's first energy code, which was developed in 1997, a lack of energy standards led to constructing buildings without energy standards provisions. Although in BC, Canada, the first provincial building code introduced in 1973, BC released its first Energy Efficient Buildings Strategy (EEBS) in 2005 to perform 25% better than MNECB. Table 2.2 presents several increases in energy efficiency in the BC building codes [16]. Also, Table 2.3 summarizes the most common measures for energy retrofitting of buildings.

Table 2.2, Energy efficiency improvement in BC [16]

| Regulation | Enacted | First compliance deadline | Standard referenced | Estimated performance gain over MNECB |
|---|---|---|---|---|
| BCBC (reg #140/73) | 1973 | Sep 1, 1973 | No comprehensive requirements for EE | N/A |

| Regulation | Enacted | First compliance deadline | Standard referenced | Estimated performance gain over MNECB |
|---|---|---|---|---|
| BCBC (reg #383/93) | 1993 | Feb 21, 1994 | Insulation requirements (Part 9 only) | N/A |
| BCBC-2006 (#216/2006) | July 17, 2006 | Dec 15, 2006 | No comprehensive requirements for EE | N/A |
| BCBC-2006 r2 | Apr 15, 2008 | Sep 5, 2008 | ASHRAE 90.1- 2004 | 23% |
| BCBC-2012 (#264/2012) | Sep 7, 2012 | Dec 20, 2012 | ASHRAE 90.1- 2004 | 23% |
| BCBC-2012 r2 (#167/2013) | Apr 5, 2013 | Dec 20, 2013 | ASHRAE 90.1- 2010 | 33% |
| - | - | - | NECB 2011 | 37% |
| BCBC-2018 r2 | Aug 24, 2018 | Dec 10, 2018 | ANSI/ASHRAE 90.1-2016 | Requiring net-zero energy ready buildings in the BCBC by 2032 |

Table 2.3, Common energy retrofitting measures

| Measures | Details | References |
|---|---|---|
| Building Envelope Upgrades | Upgrading exterior / interior wall insulations<br>Upgrading doors and windows<br>(for example, double/triple-glazing windows)<br>Upgrading ceiling insulations | [6], [9]–[15] |
| Ventilation Systems Upgrades | Improving of heating, cooling, and lightning system<br>Application of central heating | [10], [11], [14] |
| Application of Renewable Energy | Change of old boilers with energy-efficient boilers and application green energy power | [9]–[11], [13] |
| Improving air-tightness issues | Retrofitting the cracks on walls or other members of buildings leading to air leakages | [11]–[13] |
| Replacing low- quality materials with high-quality materials during retrofitting process | Most of heritage and old existing building were built with low-quality materials due to lack of standards | [6] |
| Application of insulated reinforced concrete slabs/roofs | When seismic upgrading is required and based on the type of the building, insulated RC slabs can be used | [6], [37] |

| Measures | Details | References |
|---|---|---|
| Design changes | For example, benefit of solar gain and daylight, etc. by removing or adding a wall/window | [10], [15] |

## 2.2. Seismic Retrofitting

It is very important to preserve social, cultural, political and economic aspects of old buildings before beginning any intervention. Since heritage buildings do not meet the current building codes [17], they are primarily vulnerable to seismic events [18]. Therefore, seismic retrofitting of these structures requires effective solutions with minimal intervention and maximal reversibility wherever it is possible [17], [18]. A reversible method is that a method when removed, the original aesthetic of the building will remain and not compromise the ability of later interventions [19].

## 2.2.1. Seismic Retrofitting Methods

Seismic retrofit solutions should reinforce both the static and dynamic properties of the members and make them more resistant to damages caused by earthquake [20]. To this aim, there are several established practices for seismic retrofitting as outlined below.

### 2.2.1.1. Common Retrofitting Solutions

The common solutions that may be used in seismic retrofitting of existing buildings are a) reinforcing connections with near-surface mounting (NSM) [21]–[26]; b) increasing shear capacity by adding shear reinforcement rebars [27]; c) strengthening of exterior walls by fibre-reinforced cementitious matrix (FRCM) and fibre-reinforced plaster [28]–[30]; d) reinforcing flooring system by adding oriented strand boards (OSB) and cross-laminated timber (CLT) [31], [32]; e) using sandwich columns for reinforcing brick masonry columns [33]–[35] and; f) reinforced cement jacketing for columns and walls of historical unreinforced masonry (URM) buildings [36]–[39].

The following paragraphs present some case studies that used common methods as seismic retrofit solutions. All these case studies are masonry constructions. Depending on the type of buildings and possibility, these interventions were used.

**a) NSM method**

Near Surface Mounting (NSM) is an effective technique that applied basically for the strengthening of reinforced concrete (RC) beams and columns. This technique by improving flexural, shear strength and ductility, increases the seismic performance of old-type RC frames [21], [22]. The NSM technique involves drilling shallow grooves along the concrete cover and placing steel or fibre-reinforced polymer rods in those grooves. The grooves are then filled with an epoxy adhesive or cement grout [23], [26].

In wood frame buildings, repair and strengthening of connections are one of the main solutions. NSM has the potential of being reversible and invisible. This method with infill smooth rebars is used to retrofit traditional timber structures, shown in Figure 2.1 [24]. In a study for strengthening connections self-tapping screws, steel plates, GFRP sheets and NSM method were used [25]. Pull-out tests showed that the initial strength of the connections was increased and the NSM technique was capable of solving the need for adequate anchorage length problems [25].

Figure 2.1, Near Surface Mounted (NSM) technique with steel flat bars [24]

**b) Added shear reinforcement rebars**

In another state-of-the-art method, the role of steel rebars shear reinforcement in high-performance self-compacting concrete (SCC) was addressed [27]. The steel rebars were placed in SCC beams by using the NSM concept. The difference between this method and NSM is that the rods were placed in the concrete beam before casting. Results show the moment capacity of the casted NSM concept beam is close to the normal beam (Tables 2.4 and 2.5). Beam1 in Figure 2.2 shows the normal beam with ordinary stirrups and Beam3 in Figure 2.3 presents the applied steel rebars as shear reinforcement in SCC beams.

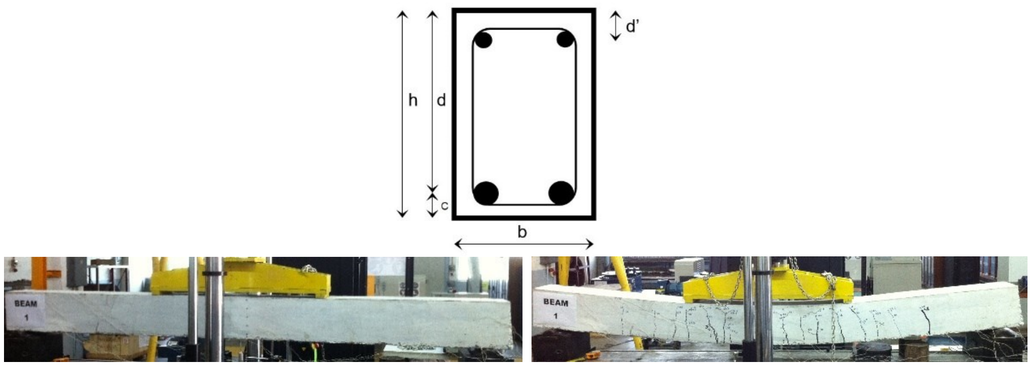
Although this study addressed the application of shear reinforcement rebars in RC beams, it also concluded that it is possible to strengthen shear cracks and avoid brittle ruptures of existing members without stirrups by adding steel rebars as shear reinforcements and NSM concept.

Table 2.4, Details of SCC reinforced beams [27].

| Beams Dimensions | Beams Number | Main Reinforcement Bar | Shear Reinforcement Bar | Shear Reinforcement Spacing |
|---|---|---|---|---|
| b= 20cm; h=25cm; d=22cm; c=3cm; d'=3.5cm | Beam 1 | Steel Ø 12 | Steel Ø 12 | 10 cm |
| | Beam 3 | Steel Ø 12 | Steel Ø 12 | 10 cm |

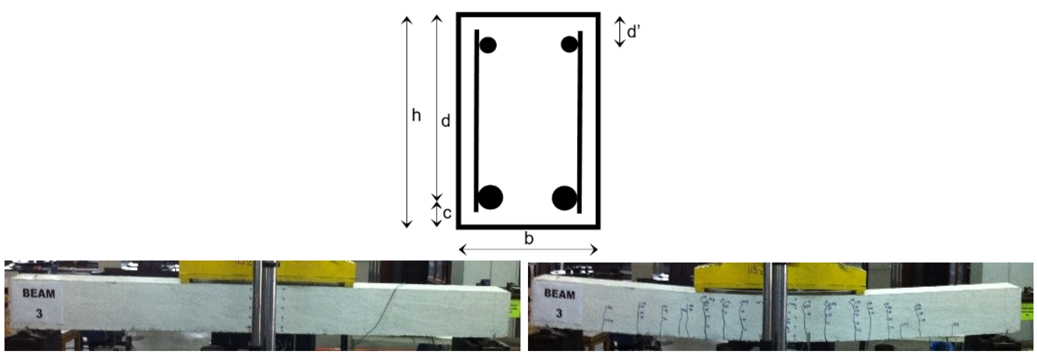
Table 2.5, Summary of results [27].

| Beams Number | Ultimate Moment (UM) (kN.m) | Design Moment (DM) (kN.m) | UM/DM | Load of First Crack (kN) | Fc (Mpa) |
|---|---|---|---|---|---|
| Beam 1 (Normal design) | 32.14 | 24.45 | 1.43 | 20 | 95.57 |
| Beam 3 (NSM concept) | 32.82 | 24.45 | 1.46 | 19.2 | 95.57 |




Beam 1

Figure 2.2, Beam 1: Normal designed SCC beam [27]




Beam 3

Figure 2.3, Beam 3: NSM concept shear reinforcement bars [27]

### c) FRCM and fibre-reinforced plaster

One of the main difficulties in seismic retrofitting is using appropriate materials for historical and URM buildings. It is recommended to use FRCM and fibre-reinforced plaster for strengthening of external walls in historical buildings [28]. FRCM is made of dry fibres embedded in an inorganic matrix, which is considered as a shear strengthening method for RC and URM structures [29]. For URM buildings, adding reinforced concrete footings under the walls and using horizontal steel beams to link the walls with a reinforced concrete slab is recommended [30]. Results have shown that (i) deformation of slabs was changed from non-rigid to rigid with diaphragm effects; (ii) the failure mechanism transformed from a local to a global formation under earthquake conditions; and (iii) more displacement capacity was recorded [30].

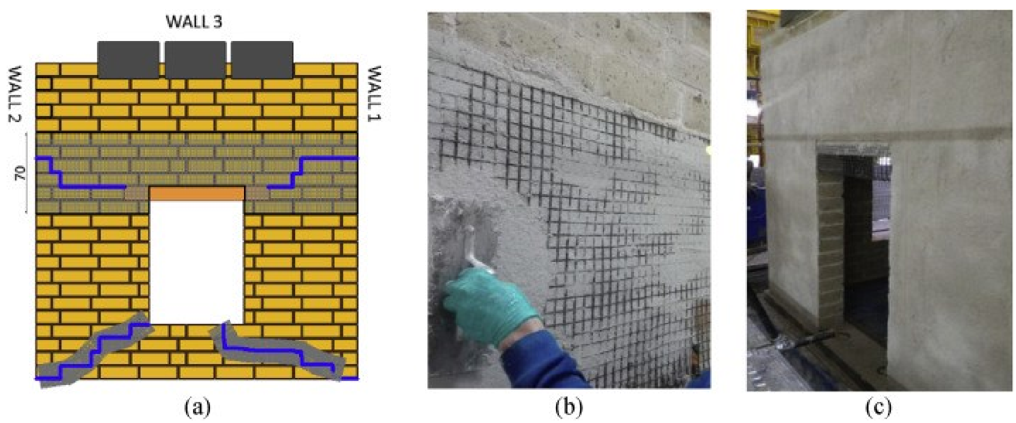



Figure 2.4, Strengthening phase: (a) FRCM layout for out of plane strengthening; (b) and (c) FRCM application for in-plane strengthening [28].

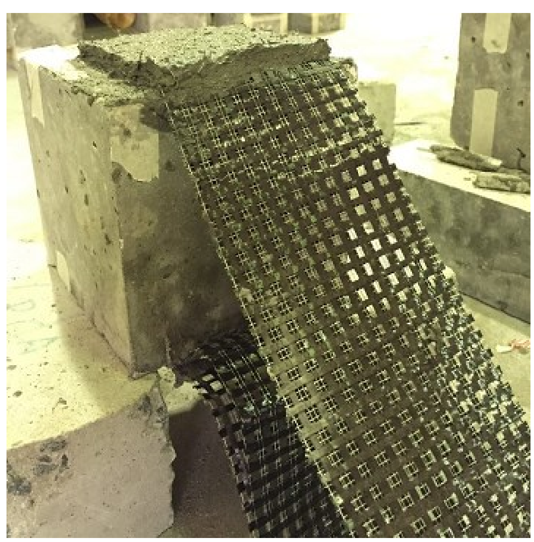


Figure 2.5, Test specimen with an FRCM double-shear connection [29]

### d) OSB and CLT

The floor and roof diaphragms in masonry buildings play a vital role in transferring the seismic loads to the shear resistant walls [31]. That is why retrofitting of low strength timber floors in heritage buildings with deficient connections is challenging and difficult.

In a study on a building with heritage value, light-weight concrete for slabs and floors was used. Out of 12 upgraded floors, seven of them were reinforced with OSB panels, two of them with CLT and the rest remained unreinforced [32]. According to results, reinforced floors showed up to seven times more stiffness compared with unreinforced floors. In specific displacements, reinforced floors with OSB panels loaded about 6 to 9 times higher than the unreinforced floor at the same displacement [32].

### e) Sandwich columns

Based on the experimental and theoretical results, the sandwich columns themselves increase to the seismic capacity of the buildings [33], [34]. In this method, basically, the column is strengthened by reinforced concrete with two techniques: either by using the hollow structural sections (HSS) as the outermost layer or by enclosing the column with reinforcement bars or both [34].

In a masonry school building built in 1970, sandwich columns were used in brick walls [35]. The sandwich columns were applied to either side of the walls with normal strength concrete (27.5 MPa) and transverse reinforcement rebars. This option improved the seismic capacity of the building by 65% [35].

Figure 2.6, Sandwich columns preparation process [34]

**f) Reinforced cement jacketing**

Reinforced cement jacketing of columns and walls is another solution for seismic retrofit of historical URM buildings which is similar to the sandwich method [36]. This method can retrofit most types of walls and columns, and it is recommended to apply on either side of the walls [37]. This technique was developed with steel mesh rebars filled by concrete and ferro-cement. Also, instead of steel rebars, fibre-reinforced polymer (FRP) mesh can be used as an alternative material [38]. FRP sheets can also be used on one side and improved the lateral resistance, in-plane strength and deformability of the walls [39].

## 2.2.1.2. Conventional Retrofitting Solutions

In some cases, engineers must use conventional seismic retrofit solutions for URM buildings. These solutions are a) surface treatment including ferro-cement, reinforced plaster, and shotcrete; b) grout and epoxy injection; c) external reinforcement; d) confining unreinforced masonry buildings using reinforced concrete tie columns; e) post-tensioning; and f) center core technique. Table 2.6 shows the efficiency, advantages, and disadvantages of each option [40].

Table 2.6, Survey summary [40]

| Technique | Efficiency In-plane | Efficiency Out-of-plane | Advantage | Disadvantage |
|---|---|---|---|---|
| Ferrocement | $F_r \rightarrow 1.5F_{ur}$<br>$D_r \rightarrow 1.7\ D_{ur}$ | Improves stability | Low cost<br>Low technology<br>Limited added mass | Space reduction<br>Arch. impact<br>Requires arch. finishing<br>Limited efficiency<br>Limited E.D. |
| Reinforced Plaster | $F_r \rightarrow 2\text{-}3\ F_{ur}$<br>Improves $D_r$ | Improves stability | Low technology<br>Limited added mass | Space reduction<br>Arch. impact<br>Required arch. finishing |
| Shotcrete | $F_r \rightarrow 3\ F_{ur}$<br>$D_r \rightarrow D_{ur}$ | Improves stability | High increment in $F_{ur}$<br>Significant improvement in E.D. | Space reduction<br>Heavy mass<br>Violation of performance level<br>Disturbance occupancy<br>Arch. impact<br>Required arch. finishing |
| Injection | Restores initial stiffness<br>$F_r \rightarrow 0.8\text{-}1.4\ F_{ur}$ | Can restores initial stiffness | No added mass<br>No effect on building function<br>No space reduction<br>No arch. impact | Epoxy create zones with varying stiffness and strength<br>High cost of epoxy<br>No significant increment in $F_r$ using cement-based grout |
| External Reinforcement | $F_r \rightarrow 4.5\text{-}10\ F_{ur}$<br>E. $D_r$ >1.5E.$D_{ur}$ | N.A. | High increment in $F_{ur}$ Prevent disintegration<br>Improves ductility and E.D. | Corrosion<br>Heavy mass<br>Violation of performance level<br>Requires arch. finishing<br>Disturbance occupancy |
| Confinement | $F_r \rightarrow 1.2\text{-}1.5\ F_{ur}$<br>$D_r \rightarrow D_{ur}$ | Prevent disintegration | Prevent disintegration<br>Improve ductility and E.D. | Not easy to introduce<br>Limited effect on $F_{ur}$<br>Required arch. finishing<br>Disturbance occupancy |
| Posttension | Improves $F_{ur}$ | Improves $F_{ur}$ | No added mass<br>No effect on building function | High losses<br>Anchorage system<br>Corrosion potential |

| Technique | Efficiency | | Advantage | Disadvantage |
|---|---|---|---|---|
| | In-plane | Out-of-plane | | |
| Center Core | $F_r \rightarrow 2\ F_{ur}$<br>$D_r \rightarrow 1.3\text{-}1.7\ D_{ur}$ | Improves $F_{ur}$ | No space reduction<br>No arch. impact<br>No effect on building function | Creation of zones with varying stiffness and strength |

*$F_r$, $F_{ur}$: lateral resistance for retrofitted and un-retrofitted specimens respectively, $D_r$, $D_{ur}$: Lateral displacement for retrofitted and un-retrofitted specimens respectively, E.D.: energy dissipation*

#### 2.2.1.3. Biological Decay and Chemical Corrosion; Preliminary Solutions

In Canada, many historical buildings with the age of 80 - 100 years old have been constructed with extensive amounts of timber and clay brick masonry [41]. Since the two main factors leading to a lack of seismic resistance are biological decay and chemical corrosion, preserving wooden parts from these threats are very important [42], [43]. In order to solve these problems, i) the existing damages should be classified, ii) the cause of each damage type should be elaborated; then, iii) by selecting compatible materials, vulnerable members can be reinforced [44]. For example, the compatible materials for retrofitting of timber structures are steel, aluminum, concrete, laminated timber, epoxy resin associated with steel or FRP bars or plates [45].

#### 2.2.1.4. Summary of Solutions

As can be seen, there are various methods for seismic retrofitting of existing structures that each of which has its own advantages, effectiveness and even its own drawbacks. Table 2.7 presents a comprehensive summary of retrofit measures on building properties [46]. In this table some methods impact more than one property of the structure. For example, to reduce deformation, an increase in stiffness leads to higher force demands. Table 2.8 shows a summary of common structural deficiencies and possible retrofitting measures [47]. Table 2.9 demonstrates some intervention techniques proper for wood frame buildings [45].

Table 2.7, Effect of local and global retrofit measures on building properties [46]

| | | Strength | Stiffness | Ductility | Irregularity | Force demand | Deformation demand |
|---|---|---|---|---|---|---|---|
| **Local Measures** | Concrete jacket | √ | √ | √ | | * | |
| | Steel jacket | √ | | √ | | | |
| | FRP jacket | √ | | √ | | | |
| | Post-tensioning | √ | | √ | | | |
| | Strength reduction | * | | | | | |
| **Global Measures** | New frames, shear walls, braces | √ | √ | | √ | * | √ |
| | Mass removal | | | | √ | √ | * |
| | Partial demolition | | | | √ | √ | |
| | Isolation | | | | √ | √ | √ |
| | Dampers | | √ | | | * | √ |
| | Expansion joints | | | | √ | | |
| | Connect independent sections | | | | √ | | |

*The symbols √ and * indicate respectively a possible beneficial or detrimental effect; the extent of which will depend on the specific case.*

Table 2.8, Common structural deficiencies and strengthening measures. [47]

| Types of Structures | Deficiencies | Strengthening Measures |
|---|---|---|
| Unreinforced masonry (non-ductile) | - low shear resistance of walls<br>- poor connections of diaphragms to walls<br>- inadequate reinforcement in diaphragms | - add reinforced concrete walls or steel braces<br>- add ties between diaphragms and walls<br>- reinforce diaphragms |
| Non-ductile moment-resisting frames | - week columns, strong beams<br>- low joint shear resistance<br>- may be susceptible to P-delta effects<br>-slabs without beams<br>- susceptible to punching shear | - increase column size or add walls or braces<br>-same as above<br>- same as above<br>- add walls or braces |
| Other types of structural deficiencies | - soft storey<br>- large torsional eccentricity<br>- insufficient lateral stiffness | - add walls or braces<br>- add walls or braces to reduce eccentricity<br>- stiffen with shear walls or braces |

| Types of Structures | Deficiencies | Strengthening Measures |
|---|---|---|
| | - susceptibility of short columns to shear failure | - strengthen column or remove short column effect |

Table 2.9, Interventional measures [45]

| Measures | Details and Conditions |
|---|---|
| Removal method | For advanced decay condition, when retrofitting by other measures are not possible or not reasonable |
| Dismantling and replacing | Only in special cases when conservation by other measures such as repair are not possible |
| Addition of elements | When structures are required to be reinforced regarding higher loads coming from a new use |
| Prosthesisation: *substituting an element with part of a single member* | At the extremities of members, near the supports and connections, where advanced states of degradation due to biotic attack has happened |
| Sealing | In timber structures, by using epoxy adhesive and reinforcement bars or the simple filling of voids with a prepared putty, new wood elements can be bound to the original timber element |
| Repair of cracks | By application of bolts, straps, FRP wraps and epoxy resins |
| Repair and strengthening of connections | It is a good solution for traditional timber structures and it can be applied to connections when conservation is desired |
| Strengthening of sections | (i) Timber: *by applying an additional timber member to the original one and connecting both members using traditional timber carpentry or using steel connectors*<br>(ii) Steel: *by adding or inserting various types of steel products such as bars, plates or profiles in any side of a member in order to increase loading capacity. Appropriate to use in the tension and compression zone*<br>(iii) FRPs: *the same as application of steel reinforcements*<br>(iv) Epoxy: *suitable to increase section size by adding epoxy resin and connecting it to the beams with steel or FRP bars as shear reinforcements/connectors*<br>(v) Concrete: *casting of a concrete slab on a timber floor to build a composite system* |
| Post-tensioning | Can be applied to both roof and floor, where lack of bearing capacity in bending was observed |
| Stiffening to in-plane action: *to increase global stability of the building, where roof and floor work as diaphragm* | (i) Connection of a new layer of timber planks over the existing;<br>(ii) Cast of a concrete slab over the timber planking;<br>(iii) Connecting of a layer of diagonally crossing steel strips over the planking;<br>(iv) The same using fibre reinforced polymers. |

In this study, the author tried to find the best solution for the case study based on previous research in both reducing energy consumption and increasing seismic resistance. This solution is discussed in detail in the following chapter.

# Chapter 3

# A Case Study

## 3.1. Objectives

The primary objectives are:

1. Assess the impact and benefits of putting energy and seismic retrofit at the same time in existing buildings.
2. Develop an approach to design and select the best solution for energy and seismic retrofitting simultaneously.

## 3.2. Methodology

The method used in this case study is as follows:

**a) Initial assessments:** Before any action, the building must be assessed externally for seismic and energy performance. The assessments should identify the building deficiencies for both seismic and energy upgrades.

**b) Needs and wants:** After initial assessments, the needs and wishes of the client as well as the project budget for retrofit solutions should be considered.

**c) Retrofit solutions:** In this phase, energy and seismic solutions would be identified and appropriately selected. To this aim, some considerations should be taken into account as outlined below .

*Energy Considerations:* As the first step, the details of installed insulation for the exterior building assemblies, thermal imaging from the building at the current condition, and results of the air blower tests would be required for the passive house planning package (PHPP) to evaluate the current condition. Then, the selected energy retrofit options will be simulated using PHPP and compared based on the amount of saved energy, annual heating demand and estimated cost.

*Seismic Considerations:* Structural analysis of the current condition and finding seismic resistance deficiencies in the building are the two important preliminary measures. The seismic solution would be designed and selected based on the weakness and needs of the building, and the cost-effectiveness of the proposed solution.

d) **Cost-benefit analysis and payback period:** By comparing the annual energy cost ($E_{cost}$) before and after retrofitting, the amount of saved energy can be calculated. In this study, the direct payback period (PBP) is calculated from the saved energy costs and the total retrofitting cost. To this aim, the following equations are used:

$$E_{saved} = (E_{cost})_{Before} - (E_{cost})_{After} \qquad (3.1)$$

$$E_{cost} = H_D \times g_{energy} \times TFA \qquad (3.2)$$

*Where:*

$E_{saved}$ = the saved costs from the amount of saved energy
$E_{cost}$ = annual energy cost;
$H_D$ = annual heating demand;
$g_{energy}$ = energy costs;
$TFA$ = treated floor area of the building

$$PBP = R_{Total} / E_{saved} \qquad (3.3)$$

*Where:*

$R_{Total}$ = total retrofitting costs;
$E_{saved}$ = saved energy costs

## 3.3. Building Description

Figure 3.1, North façade of the building at Fisgard Street

The case study is a two-story heritage building located in Victoria, BC, Canada, has a footprint of about 7,500 square feet. The first floor is used for commercial purposes and the second floor consists of residential units. All portions of the building are constructed of load-bearing URM walls, with some load-bearing wood framing at interior walls and mezzanines. Roofs and floors are constructed of wood decking on wood joists. The exterior walls are constructed of old clay bricks. On the interior side, there is no insulation on the wall assemblies except a layer of plaster on the bricks. This building does not have a foundation system and its flooring is slab on grade. Figure 3.2 indicates the layout of the first floor including the four stores on the north facade and the three stores on the eastern side and Figure 3.3 is the layout of the residential units on the second floor.

According to the engineers and consultants, air leakage and water penetration are the two main issues in this building leading to the deterioration of the masonry and the mortar joints. The poor conditions of the plumbing, doors and windows are a testament to this claim (Figure 3.4). The brick mouldings, windows and doors are poorly degraded from the weather and all the seals have eroded entirely. Plumbing pipes are running all the way through the walls regardless of whether they are interior or exterior walls. This creates a lot of openings and gaps in the wall assemblies. So where a wall exists, it has been punctured by all kinds of water pipes and septic pipes. Also, Figure 3.5 shows a very poor condition of the southern windows and a deck over top of an existing roof that tends to degrade. In fact, it is typically the extent of dilapidation that has occurred in the rear of the building. Figure 3.6 is an eastern view of the building in the Fantan Alley that illustrates many openings in this side of the building. In addition to the restrictions imposed by the City of Victoria, one of the reasons that retrofitting work cannot be carried out from the outside is that this alley is very narrow. In fact, the width of this alley is 90 cm and it is known as the narrowest street in the country and a side door to Canada's oldest Chinatown [48].

Besides, as Figures 3.4, 3.5 and 3.6 demonstrate, the lack of insulation in the building envelope is another main reason for losing high amounts of energy from the building. The reason that it is not possible to get an airtightness rate close to a passive house rate (0.6 ACH @ 50pa) anywhere of the many holes throughout the walls. Therefore, it is important to bring the brick back to a point where doing a proper retooling of the masonry joints and putting the new woodwork back inside is possible.

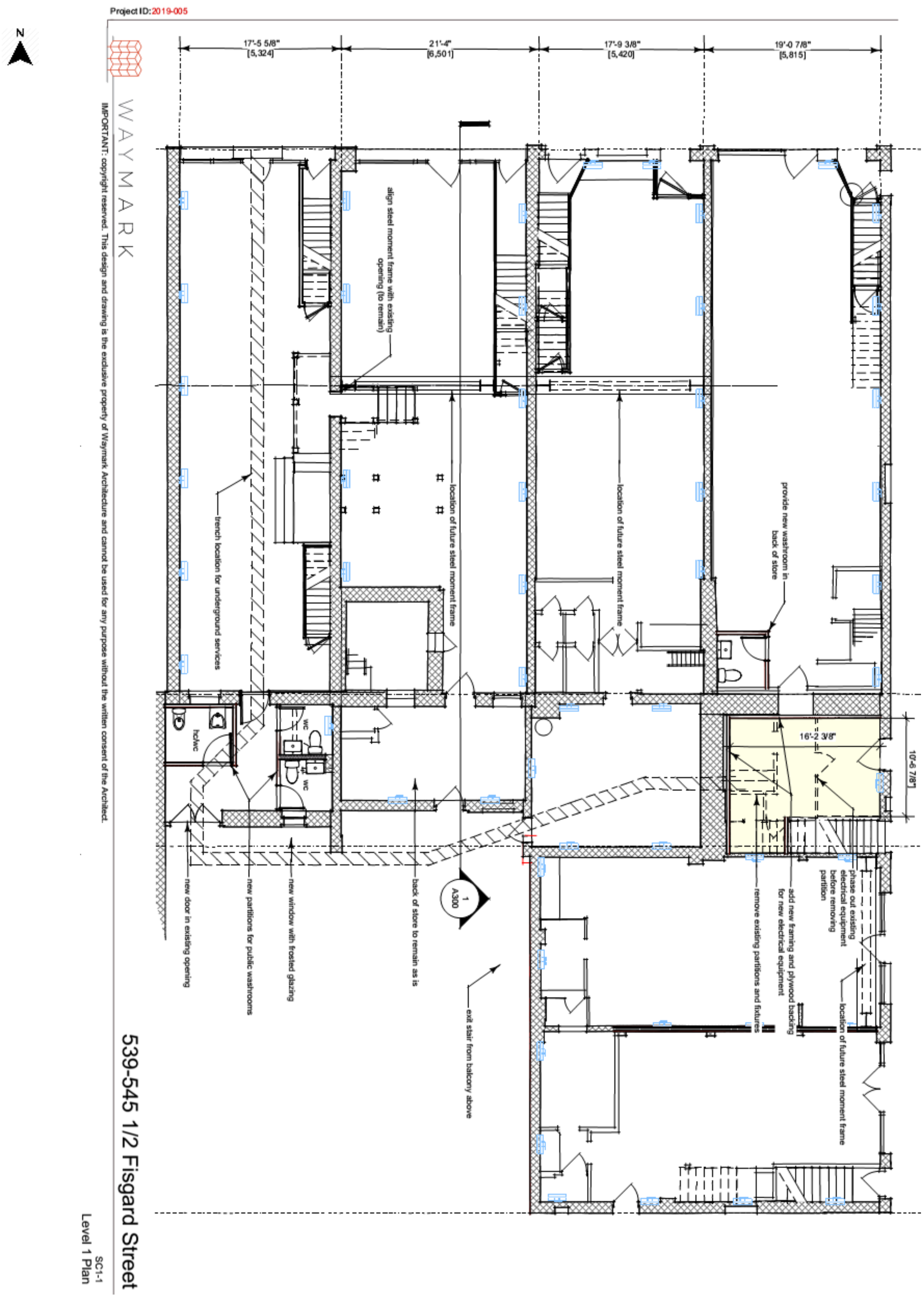



Figure 3.2, Layoiut of 1st floor of the building

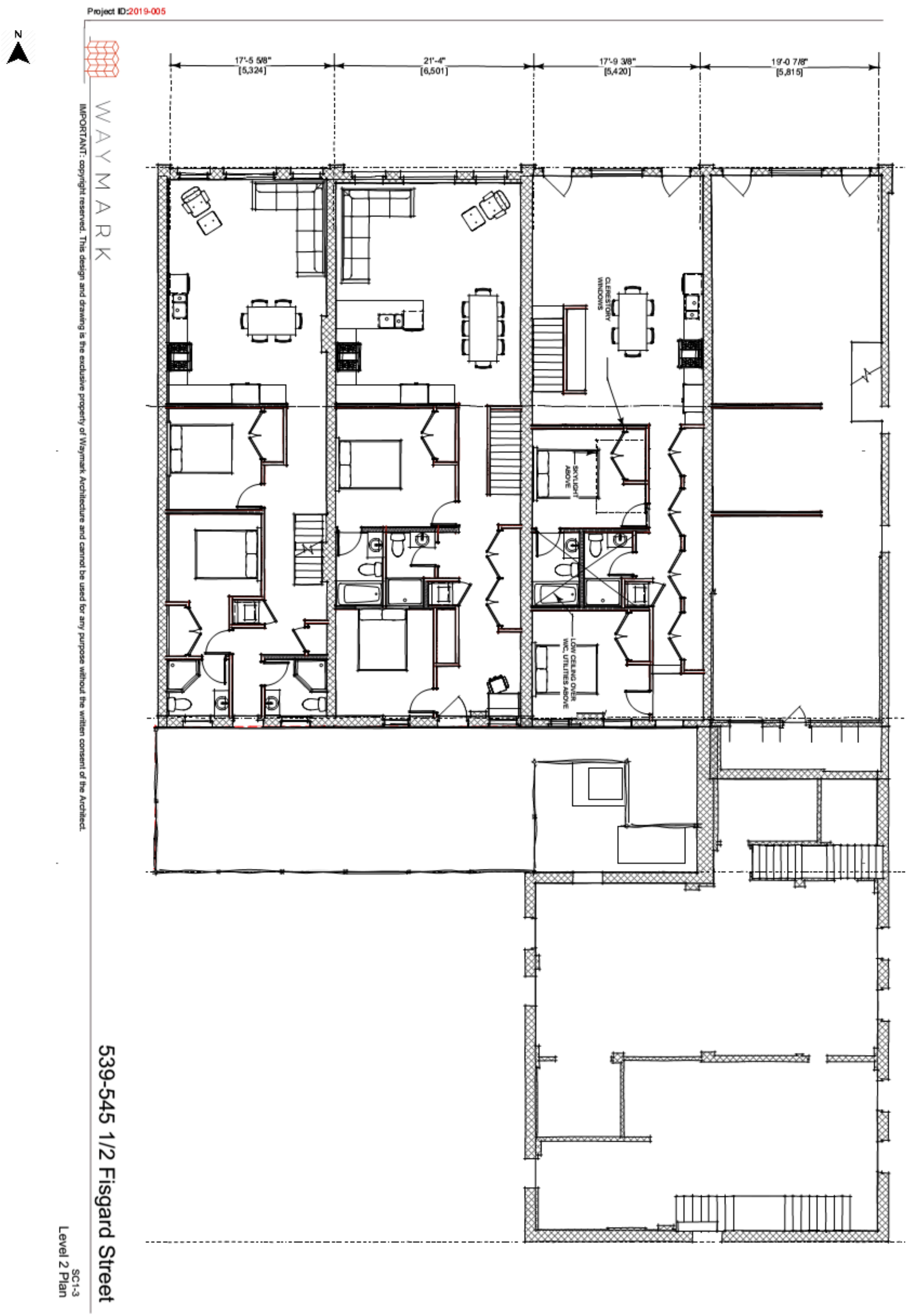



Figure 3.3, Layout of 2nd floor of the building

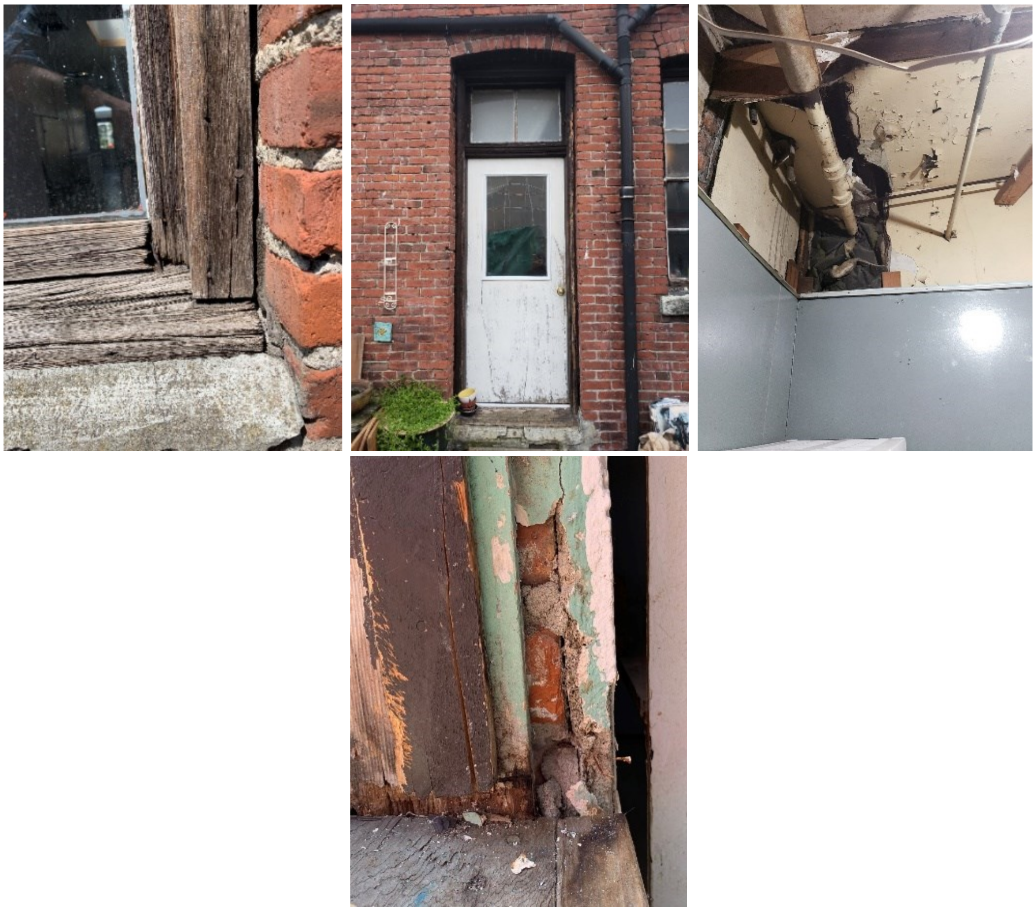


Figure 3.4, Rotted frames, gap between walls and missed seals

Figure 3.5, South façade of the building; degraded doors and windows


Figure 3.6, East façade of the building at Fantan Alley

## 3.4. Limitations and Uniquenesses

This building was selected in line with the provincial program for seismic retrofitting and reducing energy consumption. The building is one of the 406 historical buildings in Victoria, BC, Canada with heritage feature that needs an immediate retrofit. The heritage characteristics of the building led to some limitations in the retrofitting. These restrictions include i) upgrading from inside the building, ii) preservation of the facade and exterior architecture of the building, iii) strictly avoiding any renovations of the exterior of the building, and iv) using the same design of exterior doors and windows if they need to be replaced.

Technically, the lack of requirements and standards for energy and seismic retrofitting of existing buildings made this task more difficult. For these initial assessments, this building was entirely assessed by a group of structural engineers in 2017. Since it was not possible to evacuate the building entirely again for more assessments before this study, the seismic evaluation carried out in 2017 was used in this study.

## 3.5. Contributions

Seismic assessments of this building were done before the start of this study. All seismic retrofit recommendations were given to the researcher by the consulting architect. Energy and seismic design detailing of the building, evaluation of one of the residential units on the second floor of the building for energy upgrades and airtightness characteristics (using blower door test apparatus), and overall visual condition assessment were carried out during this study.

## 3.6. Initial Assessments of the Building

There is currently no central heating and cooling system in the building, and no apparent insulation in the walls, floors and roof. The existing seismic force resistance for the building is provided by the unreinforced masonry perimeter walls. The lateral loads imparted on the building by seismic accelerations are transferred to the walls, the roof and floor diaphragms. The connections from the walls to the floors and roof are required to resist in-plane shear forces and out-of-plane tension forces. It is important to stabilize the walls and transfer shear loads. As is typical for buildings of this era, these connections are likely adequate for less than 15% of current Code specified seismic forces.

## 3.7. Energy Part

### 3.7.1. Needs and Wants

After analyzing the energy demand of the building using Passive House Planning Package (PHPP) software, the amount of heating demand is 595.6 kWh/m²y (Figure 3.7). This amount was formulated for the whole building as a system boundary. This system boundary includes the first-floor stores and the residential units on the second floor. In this software, structural properties of exterior walls, floors and ceiling, windows and openings, geographical location and weather data, and the rate of air-tightness resulted from the air blower test were required. To find the exact rate of airtightness, thermal bridges and vulnerable areas, air-blower tests alongside thermography were considered. Figure 3.8 shows the air blower and thermography test setup in the building. The rate of airtightness test was 23.2 ACH @ 50 pa at the initial condition.

**Passive House Verification (step-by-step)**

calculated step: 1-

Photo or Drawing

| | | | |
|---|---|---|---|
| **Building:** | 539 - 545 Fisgard St. | | |
| Street: | 539 - 545 Fisgard St. | | |
| Postcode/City: | Victoria | BC | |
| Province/Country: | Canada | CA-Canada | |
| Building type: | Unreinforced Masonry (URM) / Heritage Value | | |
| Climate data set: | CA0025a-Victoria | | |
| Climate zone: | 4: Warm-temperate | Altitude of location: | 13 m |
| **Home owner / Client:** | Canada Government | | |
| Street: | | | |
| Postcode/City: | | | |
| Province/Country: | BC | Canada | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Architecture:** | Waymark Architecture | | | **Mechanical engineer:** | Uvic-Waymark | |
| Street: | 1826 Government Street | | | Street: | Uvic-Waymark | |
| Postcode/City: | V8T4N5 | Victoria | | Postcode/City: | | |
| Province/Country: | BC | CA-Canada | | Province/Country: | BC | 1-Residential building |
| **Energy consultancy:** | Waymark Architecture | | | **Certification:** | Uvic-Waymark | |
| Street: | 1826 Government Street | | | Street: | Uvic-Waymark | |
| Postcode/City: | V8T4N5 | Victoria | | Postcode/City: | | |
| Province/Country: | BC | CA-Canada | | Province/Country: | BC | 1-Standard (only for residential buil |

| | | | | | |
|---|---|---|---|---|---|
| Year of construction: | 2019 | Interior temperature winter [°C]: | 20.0 | Interior temp. summer [°C]: | 25.0 |
| No. of dwelling units: | 8 | Internal heat gains (IHG) heating case [W/m²]: | 0.0 | IHG cooling case [W/m²]: | 0.0 |
| No. of occupants: | 30.0 | Specific capacity [Wh/K per m² TFA]: | 60 | Mechanical cooling: | |

**Specific building characteristics with reference to the treated floor area**

The PHPP has not been filled completely; it is not valid as verification

| | | | | Criteria | Alternative criteria | Fullfilled?[2] |
|---|---|---|---|---|---|---|
| | Treated floor area m² | 1320.6 | | | | |
| **Space heating** | Heating demand kWh/(m²a) | 596 | ≤ | 15 | - | no |
| | Heating load W/m² | 214 | ≤ | - | 10 | |
| **Space cooling** | Cooling & dehum. demand kWh/(m²a) | - | ≤ | - | - | - |
| | Cooling load W/m² | - | ≤ | - | - | |
| | Frequency of overheating (> 25 °C) % | 3 | ≤ | 10 | | yes |
| | Frequency of excessively high humidity (> 12 g/kg) % | 0 | ≤ | 20 | | yes |
| **Airtightness** | Pressurization test result $n_{50}$ 1/h | 23.2 | ≤ | 0.6 | | no |
| **Non-renewable Primary Energy (PE)** | PE demand kWh/(m²a) | 642 | ≤ | - | | - |
| **Primary Energy Renewable (PER)** | PER demand kWh/(m²a) | 1005 | ≤ | 30 | 45 | no |
| | Generation of renewable energy (in relation to projected building footprint area) kWh/(m²a) | 0 | ≥ | 120 | 198094500120 | |

[2] Empty field: Data missing; '-': No requirement

I confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The PHPP calculations are attached to this verification.

Passive House Premium? no

| Task: | First name: | Surname: | Signature: |
|---|---|---|---|
| 1-Designer | Mohsen | Kobraei | |
| Waymark Architecture | Issued on: June 15th, 2019 | City: Victoria, BC, Canada | |

Figure 3.7, PHHP verification spreadsheet

Since the building has no insulation on it and is in poor condition, all the external walls and other exterior building assemblies must be insulated. Although there is no legal requirement for energy upgrading of existing buildings, the owner intends to reduce the building energy consumption by 50%.

Figure 3.8; Blower door and thermography tests

## 3.7.2. Energy Solutions

To find a solution for energy retrofitting in this building, many considerations should be undertaken, for example, i) limitations for heritage buildings announced by the City of Victoria, ii) feasibility and compatibility of retrofit option for such buildings with minimum intervention, and iii) cost of the option. Different options have been studied as energy retrofit solutions. Hence, the five practical proposed options analyzed with PHPP software to determine the exact amount of energy saving. Meanwhile, the cost of each option was calculated to select the cost-effective energy retrofit solution.

Five options are proposed for the exterior walls and these are detailed in Figure 3.9. Since in this research the seismic and energy retrofitting of the building were supposed to be done simultaneously, the flooring system of the second level and roof was designed by different specific considerations. Therefore, only one option was provided for the second floor and roof. The details of which are shown in Tables 3.2 and 3.3. Also, on the first floor, only the flooring system of one store, which has wooden finished flooring on the slab, could be upgraded (Table 3.1). Other stores have a slab on grade flooring systems.

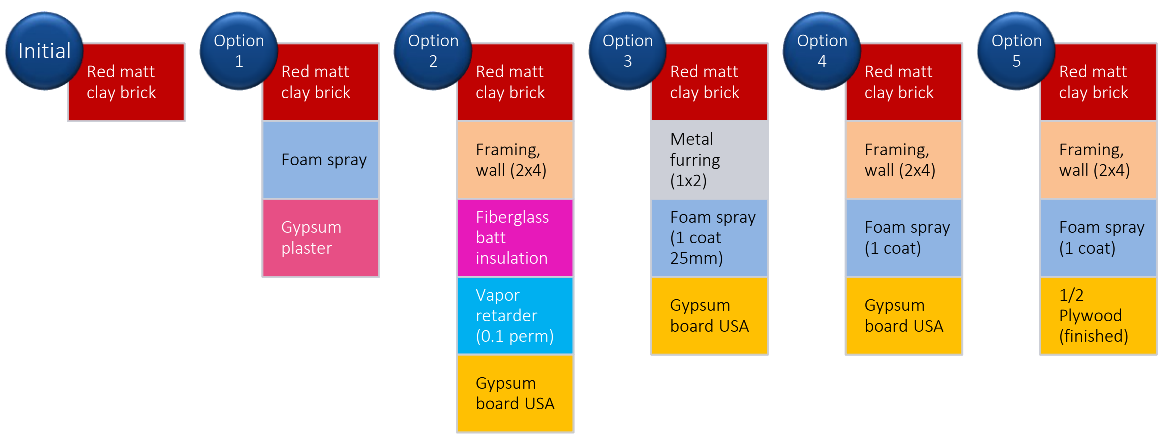



Figure 3.9; Energy retrofit options for external walls

### 3.7.2.1. Results from PHPP for Proposed Energy Solutions

Tables 3.1 to 3.3 present all details of floors and roof options including the total cost and thermal resistance value (R-Value) of each option. At the first floor and in store No. 543, a layer of extruded polystyrene insulation (XPS) with 51 cm is installed after pouring cast in place (CIP) concrete with a thickness of 102 cm. The total cost and thermal resistance (R-value) of this floor assembly are $2,672 and 8.5 respectively. Since it is not feasible to upgrade the entire flooring system on the first floor, the required area (RAU) of this floor is much less than the RAU of the second floor. At the second floor, more upgrades have been considered. Wood flooring is the finished layer on the floor of the second level. Underneath the finished layer, a layer of plywood is placed. Fiberglass insulation batts were embedded on T-beam joists and a layer plaster with 19 mm thickness completed this upgrading. The total cost and thermal resistance (R-value) of these layers are $94,932 and 25.8 respectively.

Table 3.1, Details of 1st floor (store #543), cost estimation and thermal resistance

| **Layers** | **Quantity** | **T mm** | **λ W/m·K** [49] | **Unit Price** [50] | **RAU m²** | **Cost of Unit*** | **R-Value** | **Cost per m²** |
|---|---|---|---|---|---|---|---|---|
| CIP Concrete | 1 | 102 | 2.3 | $3.52 | 85.95 | $308 | 8.5 | $31 |
| XPS Insulation | 1 | 51 | 0.04 | $27.5 | 85.95 | $2,364 | | |
| | | | | | | Total: $2,672 | | |

*T: thickness; λ: lambda, RAU: required area of unit, $: Canadian dollars*

Table 3. 2, Details of 2nd floor, cost estimation and thermal resistance

| **Layers** | **Quantity** | **T mm** | **λ W/m·K** [49] | **Unit Price** [50] | **RAU m²** | **Cost of Unit** | **R-Value** | **Cost per m²** |
|---|---|---|---|---|---|---|---|---|
| Wood Flooring (finished) | 1 | 21 | 0.18 | $154 | 544.34 | $83,828 | 25.8 | $174.5 |
| 3/4 Plywood | 1 | 19 | 0.13 | $13 | 544.34 | $7,076 | | |
| Fiberglass Batt Insulation | 1 | 300 | 0.043 | $7.4 | 544.34 | $4,028 | | |
| T-beam Joist | Existing | 450 | 0.18 | 0 | 190.52 | $0.00 | | |
| Plaster Ceiling | Existing | 19 | 0.8 | 0 | 544.34 | $0.00 | | |
| | | | | | | Total: $94,932 | | |

The roof assembly in the building has the highest R-value with 43.8. This assembly starts from the existing asphalt as the exterior side layer, 19 mm sheathing plywood, 300 mm fibreglass batt insulation, vapor retarder (0.1 perm), 15.5 mm plywood, and ends to12 mm gypsum board as the interior layer. The total cost of upgrading roof is $26,066. That is $47 per square meter of roof area.

Table 3. 3, Details of roof, cost estimation and thermal resistance

| **Layers** | **Quantity** | **T mm** | **λ W/m·K** [49] | **Unit Price** [50] | **RAU m²** | **Cost of Unit** | **R-Value** | **Cost per m²** |
|---|---|---|---|---|---|---|---|---|
| Asphalt | Existing | 200 | 0.75 | 0 | 554.17 | $0.00 | 43.8 | $47 |
| Sheathing 3/4 Plywood | 1 | 19 | 0.13 | $13 | 554.17 | $7,204 | | |
| Fiberglass Batt Insulation | 1 | 300 | 0.043 | $7.4 | 554.17 | $4,100 | | |
| Vapor Retarder (0.1 perm) | 1 | 0.152 | 2.3 | $1.74 | 554.17 | $964 | | |
| 5/8 Plywood | 1 | 15.5 | 0.13 | $11.3 | 554.17 | $6,262 | | |
| Gypsum Board USA | 1 | 12 | 0.18 | $13.6 | 554.17 | $7,536 | | |
| | | | | | | Total: $26,066 | | |

According to the external wall assemblies, Tables 3.5 to 3.9 present all details of exterior walls options. In PHPP, in order to obtain the annual heating demand per square meter, the data of all building components must be entered. By considering the same floors and roof assemblies' input for all exterior wall options, results show that between them, the lowest heating demand occurred in Options 4 and 5, with 137.6 kWh/m²y. This value for Option 3 and Option 2 is less by almost 11% in comparison with Options 4 and 5. Table 3.10 and Figure 3.10 summarize expenses required and R-Value for each option. Besides, Table 3.11 and Figure 3.11 show how sensitive any upgrade is to airtightness rate of the building. These rates started from the initial condition, which is 23.2 ACH @50pa, and compared with the targeted (5 ACH), EnerPhit (1.0 ACH), and Passive House (0.6 ACH) rate. These data show how high performance sealing up helps to reduce energy consumption. It can be found that if the air leakage is not stopped, there isn't much change in energy saving. And if this rate reduced to less than 5, more energy could be saved. In other words, high-performance building envelope and high-performance sealing have a direct relationship together to reduce energy consumption.

As Figure 3.9 and Tables 3.5 to 3.9 present, Option 1 by adding 25 mm foam spray and three coats of gypsum plaster is the most expensive solution among all the proposed options. Although it may be expected that the best R-Value can be obtained at a high cost, facts and figures show the thermal resistance of Option 1 is only 60% of Options 4 and 5. Therefore, Option 2 was selected based on the viability, minimum intervention, reasonable price and acceptable heating demand compared with the remaining options.

In Option 2 along with the existing red matt clay brick, the main components of this assembly are: i) wall framing; ii) fibreglass batt insulation; iii) vapor retarder; and iv) gypsum board. Hence, by selecting this option as the best solution and calculating all the costs and expenses, $10,935 or $29.87 per square meter of total external wall areas is required to upgrade and retrofit all the external walls in both levels with the R-Value of 10.3. For the first level flooring system, $31 per square meter is required. These costs for the entire area of the second level flooring and roof are $174.4 and $47 per square meter, respectively.

On the other hand, as a hypothesis, it was analyzed that by spending $10,495 in insulation materials for floors and roof ($8.86 per square meter), without improving external walls, it is possible to reduce 40% in annual energy demand of the whole building. It can be found that how effective any small change is to reduce energy consumption. Figures 3.12 compares heating losses and heating gains of the selected solution with the initial condition on the same scale. As predicted, openings play a crucial role in heating gains in the summer. This leads to increased cooling load in energy consumption since latent heat must be removed from the indoor spaces. This value was 489.1 kWh/m²y and reduced to 108 kWh/m²y. That is 4.5 times reduction. In addition, Figure 3.12 shows that the roof and ceiling, external walls and ventilation have important impacts on energy losses.

Another important factor that affects interior temperature is the frequency of overheating in summer. The summer interior temperature is highly dependent on climatic region, openings such as windows, shadings, building orientation, building ventilation system and heating sources [51]. Except for natural and geographical conditions, all of the above are at their worst. Hence, the frequency of overheating of the building in the initial condition was 10%. This value after retrofitting will go to 3%. That is a big change and takes the building from a poor assessment to a good assessment based on the Passive House standard. The following table shows a classification of summer thermal comfort based on the frequency of overheating.

Table 3.4, Assessment of the frequency of overheating [51]

| Frequency of overheating at 25 º C | Assessment |
|---|---|
| > 15% | Catastrophic |
| 10 – 15% | Poor |
| 5 – 10% | Acceptable |
| 2 – 5% | Good |
| 0 – 2% | Excellent |

Figure 3.13 illustrates a comparison between Passive House and EnerPhit standards with retrofitted and initial conditions for both airtightness rate and heating demand. The average air exchange rate represents infiltration in the building. The maximum acceptable value for residences based on the Passive House Standard is 0.6 ACH @50pa. This value

for retrofitted Passive House building is 1 [52]. As discussed, the average targeted exchange rate was considered 5 ACH@50pa from the initial value of 23.2 ACH@50pa. Passive House standard has the same policy for heating demand. The upper limit for the specific annual heating demand for Passive House buildings is 15 kWh/m²y [51]. Based on the EnerPhit, this value for retrofitted buildings equal to Passive House in cool-temperate is 25 kWh/m²y [52].

Table 3.5, Details of Option 1, cost estimation and thermal resistance

| **Layers** | **Quantity** | **T* mm** | **λ* W/m·K** [49] | **Unit Price** [50] | **RAU* m²** | **Cost of Unit*** | **R-Value** | **Cost per m²** |
|---|---|---|---|---|---|---|---|---|
| Red Matt Clay Brick | Existing | 300 | 1.2 | - | 414.03 | $0.00 | 7.0 | $156 |
| Foam Spray (1 coat 25mm) | 1 | 25 | 0.035 | $19 | 414.03 | $7,866 | | |
| Gypsum Plaster (3 coats) | 1 | 19 | 0.18 | $137 | 414.03 | $56,722 | | |
| | | | | | | Total: $64,588 | | |

*T: thickness; λ: lambda, RAU: required area of unit, $: Canadian dollars*

Table 3.6, Details of Option 2, cost estimation and thermal resistance

| **Layers** | **Quantity** | **T mm** | **λ W/m·K** [49] | **Unit Price** [50] | **RAU m²** | **Cost of Unit** | **R-Value** | **Cost per m²** |
|---|---|---|---|---|---|---|---|---|
| Red Matt Clay Brick | Existing | 300 | 1.2 | - | 414.03 | $0.00 | 10.3 | $26.5 |
| Framing, Wall (2x4) | 1 | 89 | 0.13 | $14.7 | 103.51 | $1,521 | | |
| Fiberglass Batt Insulation | 1 | 89 | 0.043 | $7.4 | 414.03 | $3,064 | | |
| Vapor Retarder (0.1 perm) | 1 | 0.15 2 | 2.3 | $1.74 | 414.03 | $720 | | |
| Gypsum Board USA | 1 | 12 | 0.18 | $13.6 | 414.03 | $5,630 | | |
| | | | | | | Total: $10,935 | | |

Table 3.7, Details of Option 3, cost estimation and thermal resistance

| Layers | Quantity | T mm | λ W/m·K [49] | Unit Price [50] | RAU m² | Cost of Unit | R-Value | Cost per m² |
|---|---|---|---|---|---|---|---|---|
| Red Matt Clay Brick | Existing | 300 | 1.2 | - | 414.03 | $0.00 | 11.8 | $30 |
| Metal Furring (1x2) | 1 | 19 | 50 | $7.31 | 103.51 | $756 | | |
| Foam Spray (1 coat 25mm) | 0.76 | 19 | 0.035 | $19 | 414.03 | $5,978 | | |
| Gypsum Board USA | 1 | 12 | 0.18 | $13.6 | 414.03 | $5,631 | | |
| | | | | | | Total: $12,365 | | |

Table 3.8, Details of Option 4, cost estimation and thermal resistance

| Layers | Quantity | T mm | λ W/m·K [49] | Unit Price [50] | RAU m² | Cost of Unit | R-Value | Cost per m² |
|---|---|---|---|---|---|---|---|---|
| Red Matt Clay Brick | Existing | 300 | 1.2 | - | 414.03 | $0.00 | 17.2 | $85 |
| Framing, Wall (2x4) | 1 | 89 | 0.13 | $14.7 | 103.51 | $1,521 | | |
| Foam Spray (1 coat) | 3.56 | 89 | 0.035 | $19 | 414.03 | $28,005 | | |
| Gypsum Board USA | 1 | 12 | 0.18 | $13.6 | 414.03 | $5,631 | | |
| | | | | | | Total: $35,157 | | |

Table 3.9, Details of Option 5, cost estimation and thermal resistance

| Layers | Quantity | T mm | λ W/m·K [49] | Unit Price [50] | RAU m² | Cost of Unit | R-Value | Cost per m² |
|---|---|---|---|---|---|---|---|---|
| Red Matt Clay Brick | Existing | 300 | 1.2 | - | - | - | 17.2 | $100.5 |
| Framing, Wall (2x4) | 1 | 89 | 0.13 | $14.7 | 103.51 | $1,521 | | |
| Foam Spray (1 coat) | 3.56 | 89 | 0.035 | $19 | 414.03 | $28,005 | | |
| 1/2 Plywood (finished) | 1 | 12 | 0.18 | $29 | 414.03 | $12,007 | | |
| | | | | | | Total: $41,533 | | |

Table 3.10, Thermal resistance (R-value) and estimation of the cost of each option

| Solution Number | R-Value | Cost Estimation |
|---|---|---|
| Initial condition | - | - |
| 1 | 7.0 | $64,588 |
| 2 | 10.3 | $10,935 |
| 3 | 11.8 | $12,365 |
| 4 | 17.2 | $35,157 |
| 5 | 17.2 | $41,533 |

Table 3.11, Sensitivity of options with different airtightness rates

| Solution | 23.2 ACH | 20 ACH | 15 ACH | 10 ACH | 5 ACH | 1.5 ACH | 0.6 ACH |
|---|---|---|---|---|---|---|---|
| 1 | 259 | 240.8 | 212.2 | 183.6 | 155 | 135 | 129.9 |
| 2 | 248.6 | 230.3 | 201.8 | 173.2 | 145 | 124.6 | 119.5 |
| 3 | 247.1 | 228.8 | 200.2 | 171.6 | 143.1 | 123.1 | 117.9 |
| 4 | 241.6 | 223.3 | 194.7 | 166.2 | 137.6 | 117.6 | 112.4 |
| 5 | 241.6 | 223.3 | 194.7 | 166.2 | 137.6 | 117.6 | 112.4 |

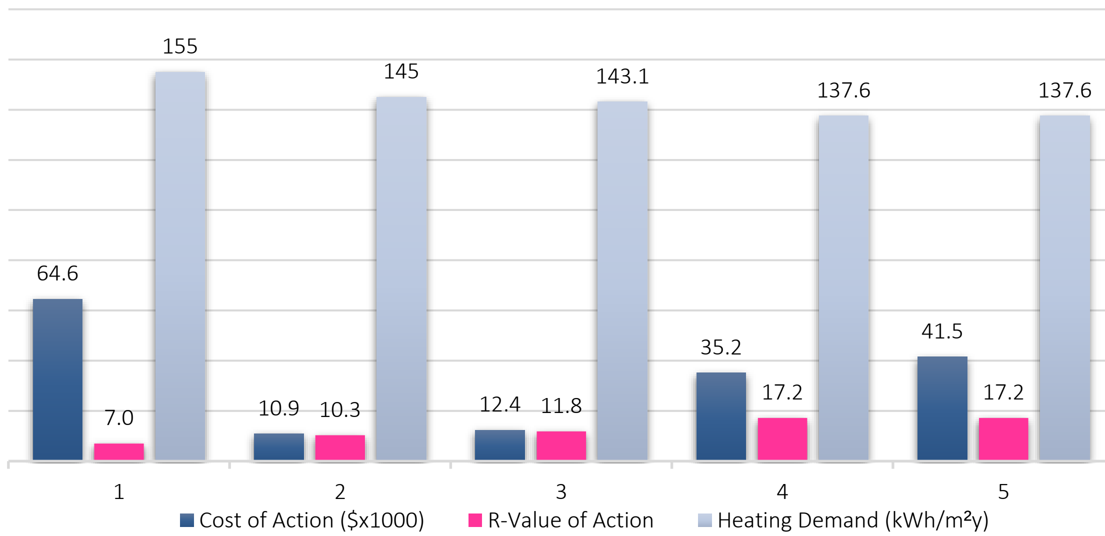



Figure 3.10, Cost estimation, R-value of each option and Heating demand of each option at the 5 ACH@50 pa

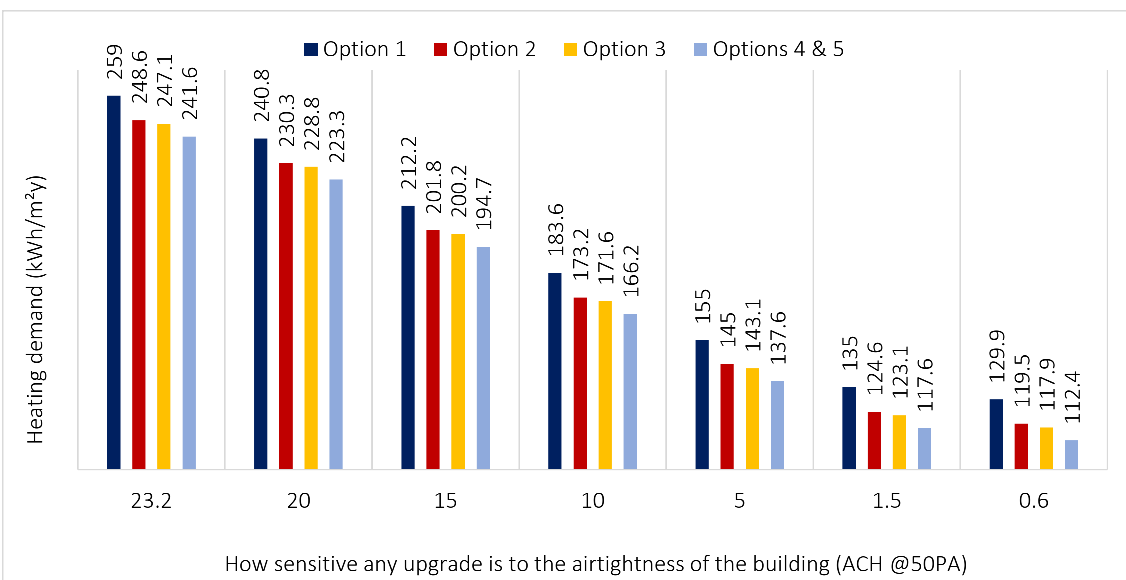



Figure 3.11, comparsion between different airtightness rates and related heating demands

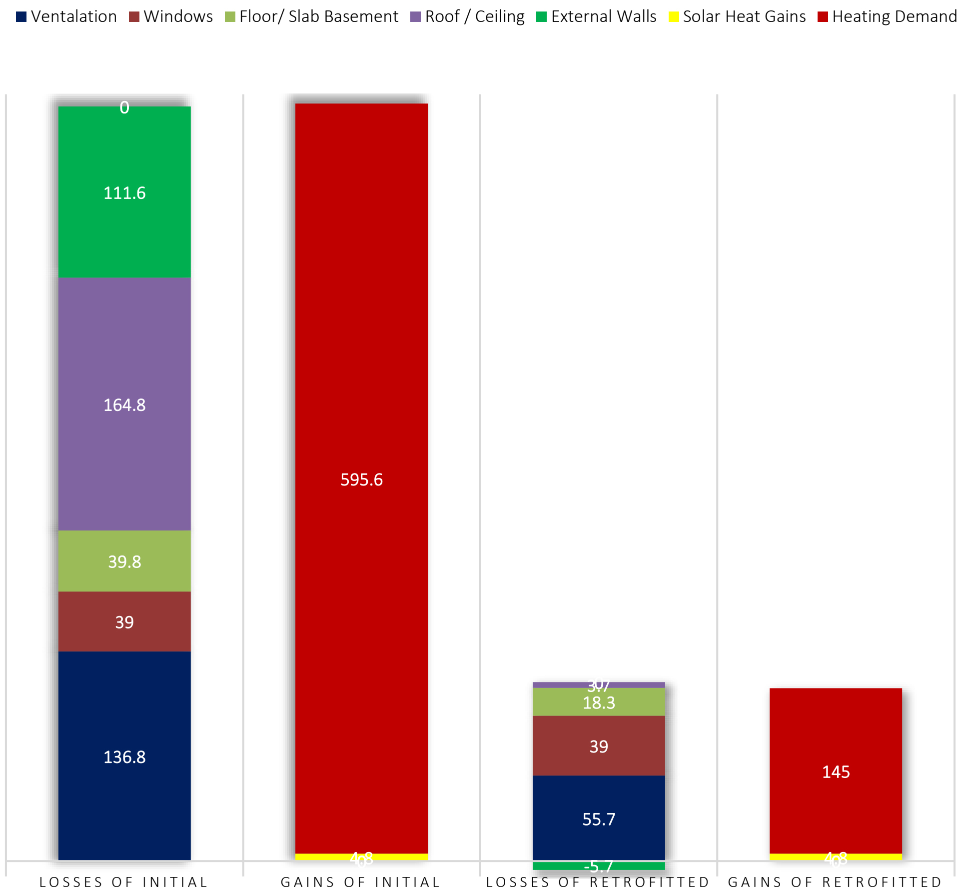
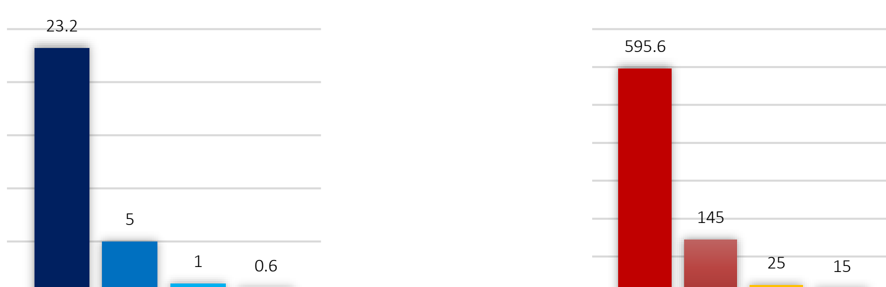



Figure 3.12, Details of comparing heating losses and gains between initial and retrofitted




| | Airtightness (ACH @50pa) |
|---|---|
| Initial Condition | 23.2 |
| Retrofitted, Option 2 | 5 |
| EnerPhit | 1 |
| Passive House | 0.6 |

| | Heating Demand (kWh/m²y) |
|---|---|
| Initial Condition | 595.6 |
| Retrofitted, Option 2 | 145 |
| EnerPhit | 25 |
| Passive House | 15 |

Figure 3.13, Comparing Airtightness rates and Heating demands between initial, retrofitted, EnerPhit and Passive House standard

## 3.8. Seismic Part

### 3.8.1. Current Conditions

Based on structural assessments done in 2017 for evaluating the safety levels of the building, this building is noncompliant with BC fire code 2012 [53], BC plumbing code 2012 [54], BC building code 2012 [55] and basic life safety standards. Also, The seismic load resisting capacity of the existing structure was compared to ASCE standard (ASCE/SEI 41-17), for evaluation and remediation of existing URM structures [56]. Since complete existing structural drawings were not available for review, this seismic review was based substantially on observations of the structural engineers and consultants' experience with similar buildings.

The structural engineers' comments assume the existing masonry walls have a minimum mortar strength of 0.2 MPa, which is typical for buildings of this vintage. Masonry walls are normally reviewed in accordance with NRC Guidelines [57], which are approximately proportional to the 60% seismic resistance level (considered the minimum for 'life safety') of the current BCBC 2012 requirements. It is anticipated that the overall capacity of the existing, interior, side, and rear walls of the building meets the requirements of the Guideline, but the street and alley facing walls would likely fall short of the requirements due to the number of openings. Based on the above, it is expected the buildings currently have an overall resistance to seismic loading of less than 15% of the seismic loading prescribed in the BCBC 2012.

### 3.8.2. Weakness and Needs

To begin any retrofitting action, the main step should be listing the primary seismic resistance deficiencies in the building. Assessments showed that i) lack of adequate diaphragm connection of the masonry and bearing walls to the floors and roof; ii) thin unreinforced masonry elements that require bracing for out-of-plane lateral loads; and iii) insufficient shear resistance of the street-facing walls are the most important weaknesses of the building.

The commentary section of BCBC 2012 suggests that existing buildings be evaluated for 60% of the current code seismic loading [55]. And, the City of Victoria commonly requires seismic upgrading to resist 70% of the current building code force levels for older, unreinforced masonry buildings that undergo a change in use or occupancy [58]. Nonetheless, due to some operational difficulties and restrictive rules such as the inability to reinforce the building from outside because of its heritage value, the best evaluated seismic upgrade would be 50%.

### 3.8.3. Seismic Solutions

If upgrades were to proceed to the 50% level, the following structural improvements would likely be required: i) strengthening of slender masonry walls by strongbacks to resist lateral loads and to maintain stability during seismic loading, ii)) improving diaphragm capacity of floors and roofs by adding steel floor straps and plywood sheathing boards; iii) adding sufficient diaphragm connections to the URM walls to resist both in-plane and out-of-plane seismic forces, and iv) adding wood shear walls including foundation and anchorage to the floors and roof. These items were listed in approximate order of greatest benefit and cost ratio. The following paragraphs and figures from 3.14 to 3.19 describe these measures in detail.

**Main floor seismic upgrade:**

1. Adding three steel wide flange moment frames (W460mm×128mm) and attached to 1000mm×600mm deep grade beams in units #541 and #543 at the Fisgard street and unit #18 at the Fantan alley.

2. Adding 21 HSS 152mm×152mm×9.5mm strongbacks from level one to level two at 3 meters spacing. Reinforcing the existing walls to achieve shear capacity between units #16 and #18.

**Second-floor seismic upgrade:**

1. Adding a layer of plywood sheathing in the floor and additional steel floor straps to transfer shear wall loads from wood shear walls to moment frames in the units #541 1/2, #543 1/2.

2. Adding two HSS moment frames around the windows in the front façade, integrated with HSS 102mm×102mm×8mm strongbacks.

3. Adding plywood shear walls in all units as indicated in Figure 10.

4. Adding 44 HSS 102mm×102mm×8mm strongbacks from level two to roof at 2 meters spacing.

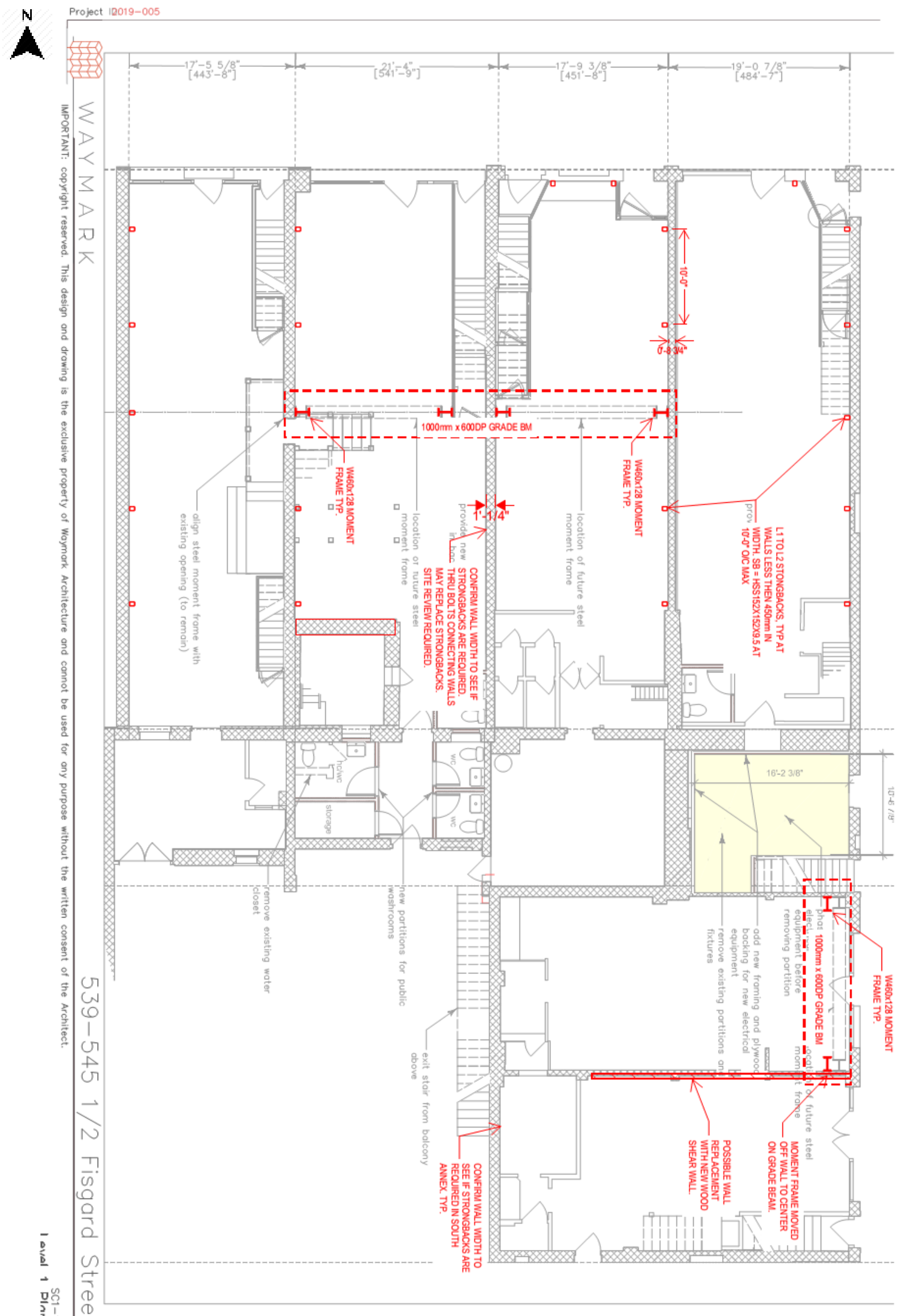



Figure 3.14, Structural seismic upgrade drawings – main floor

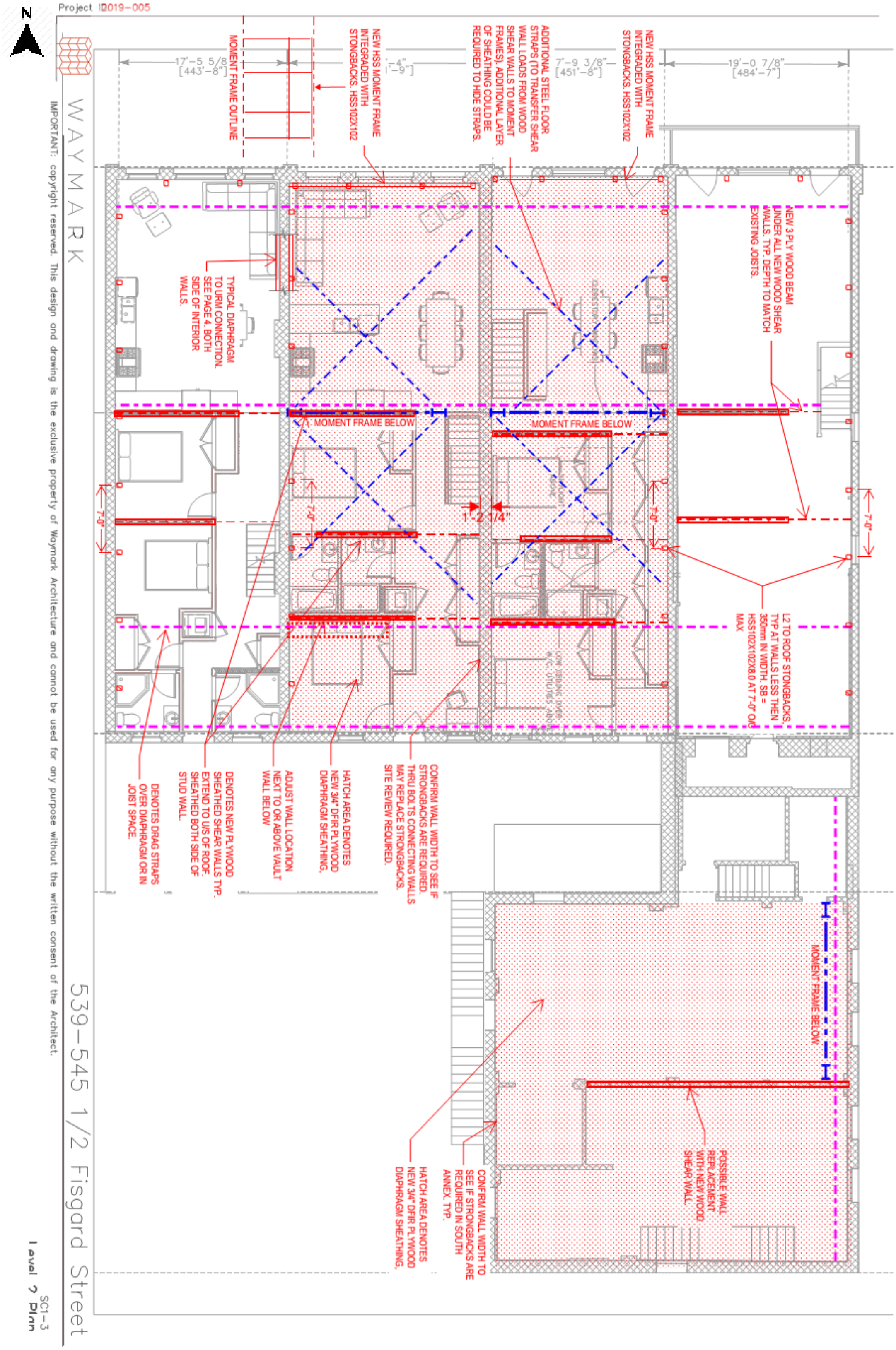


Figure 3.15, Structural seismic upgrade drawings – second floor

**Roof seismic upgrade:**

5. Adding plywood sheathing on the roof.

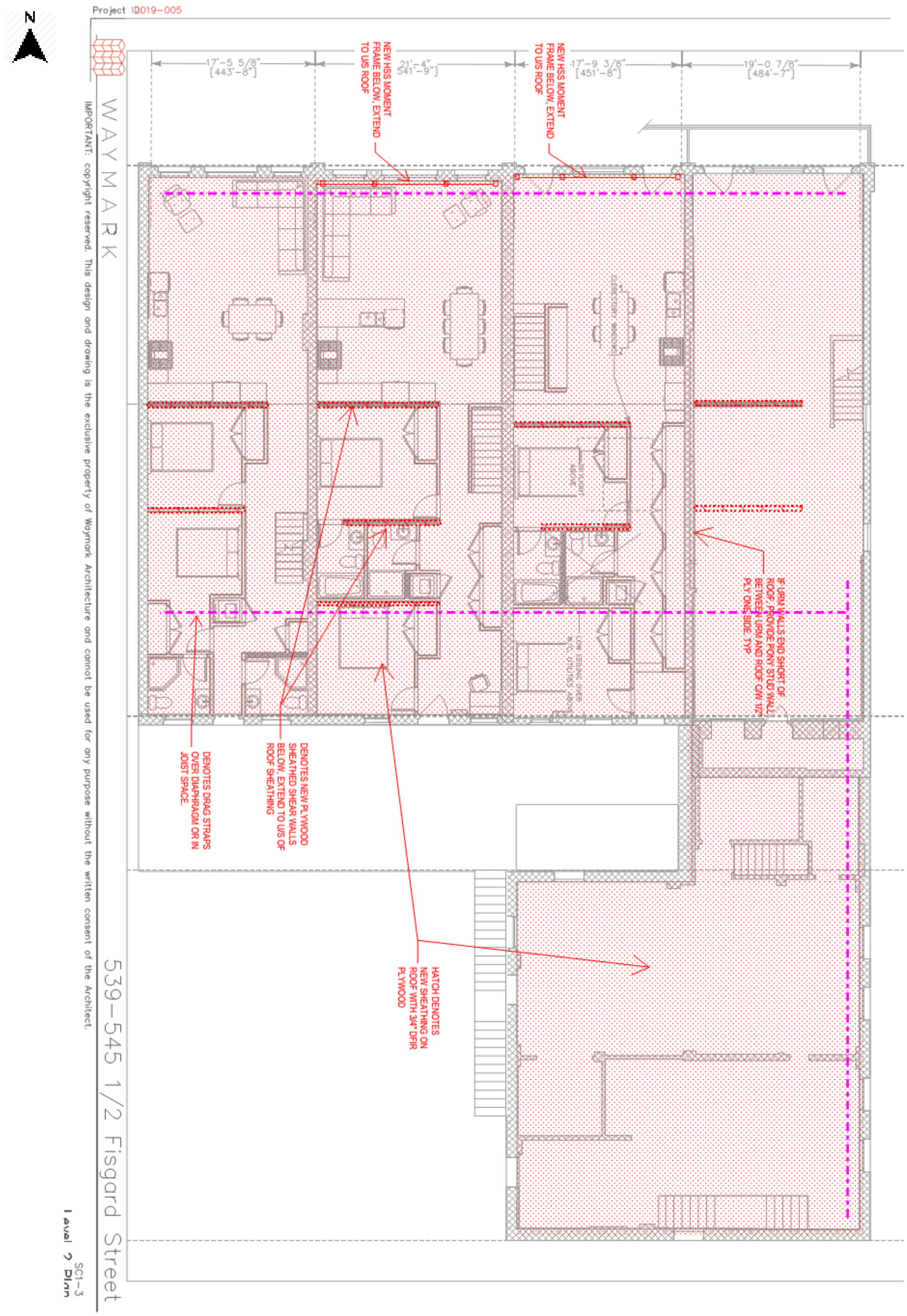



Figure 3.16, Structural seismic upgrade drawings – roof

In general, 65 HSS strongbacks on both floors are needed to make the building seismic-resistant. Each of these strongbacks will be connected to the wall with four steel brackets and linked to the other one with three more L angle brackets. It is estimated that more than 500 meters of L Angle Steel Bracket 4"×4"×1/4" will be required for this purpose. The construction costs for the listed seismic upgrades would be around $53.6 per square meter. Table 3.12 describes the cost estimation of the seismic retrofitting solution in detail. To mention, the cost of plywood sheathing was considered in the energy part as it has impacts on seismic and energy retrofitting [6], [9]–[15].

Table 3.12, Cost estimation seismic retrofitting solution

| **Materials** | **Quantity** | **Length / Height m** | **Weight kg/m** | **Unit Price** [50] | **Total Unit Price** |
|---|---|---|---|---|---|
| HSS 6"×6"×3/8" (1st floor) | 21 | 4.34 | 3.8 | 6940 $/Ton | $2,400 |
| HSS 4"×4"×5/16" (2nd floor) | 44 | 4.57 | 3.8 | 6940 $/Ton | $5,545 |
| L Angle Steel Braket 4"×4"×1/4" (1st floor) | 8 | 13 | 0.98 | 6270 $/Ton | $640 |
| L Angle Steel Braket 4"×4"×1/4" (1st floor) | 2 | 8 | 0.98 | 6270 $/Ton | $98 |
| L Angle Steel Braket 4"×4"×1/4" (2nd floor) | 8 | 14.65 | 0.98 | 6270 $/Ton | $885 |
| L Angle Steel Braket 4"×4"×1/4" (2nd floor) | 4 | 17.30 | 0.98 | 6270 $/Ton | $270 |
| L Angle Steel Braket 4"×4"×1/4" (2nd floor) | 4 | 5.70 | 0.98 | 6270 $/Ton | $590 |
| L Angle Steel Braket 4"×4"×1/4" (2nd floor) | 4 | 2.74 | 0.98 | 6270 $/Ton | $184 |
| L Angle Steel Braket 4"×4"×1/4" | 244 | 0.6 | 0.98 | 6270 $/Ton | $1,887 |
| Wide Flange Steel Column W460×128 | frame 1 | 13.85 | 128 | 5990 $/Ton | $10,620 |
| Wide Flange Steel Column W460×128 | frame 2 | 13.35 | 128 | 5990 $/Ton | $10,236 |
| Wide Flange Steel Column W460×128 | frame 3 | 10.8 | 128 | 5990 $/Ton | $8,280 |
| D. Grade Beams (Frame 1&2) 0.6m×1m | 1 | 12.545 | 2400kg/m³ | 44.10 $/m³ | $332 |

| Materials | Quantity | Length / Height m | Weight kg/m | Unit Price [50] | Total Unit Price |
|---|---|---|---|---|---|
| D. Grade Beams (Frame 3) 0.6m×1m | 1 | 5.868 | 2400kg/m³ | 44.10 $/m³ | $155 |
| Welding and Labor cost | - | 1524.2 | - | 20 $/m | $30,484 |
| * *Cost/total floor areas (TFA)* | | | | | Total: $70,800 Cost/m² *: $53.6 |

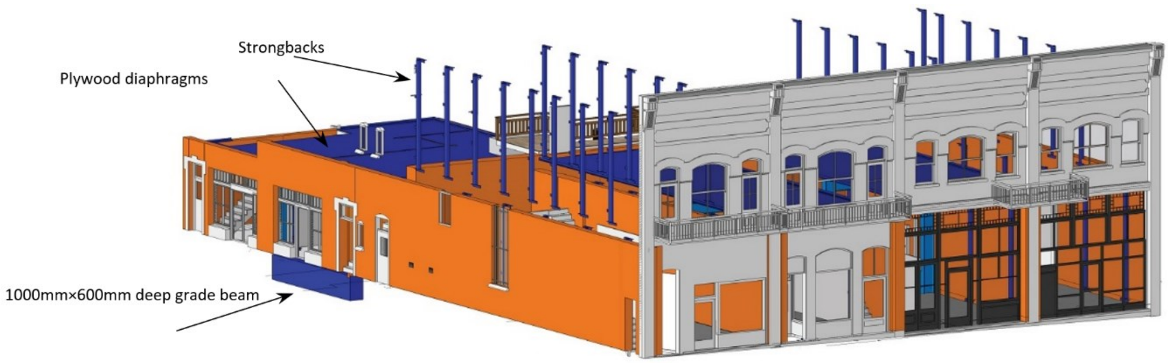



Figure 3.17, Structural seismic upgrade solution by adding HSS strongbacks, moment frames and plywood sheathings, north-east view

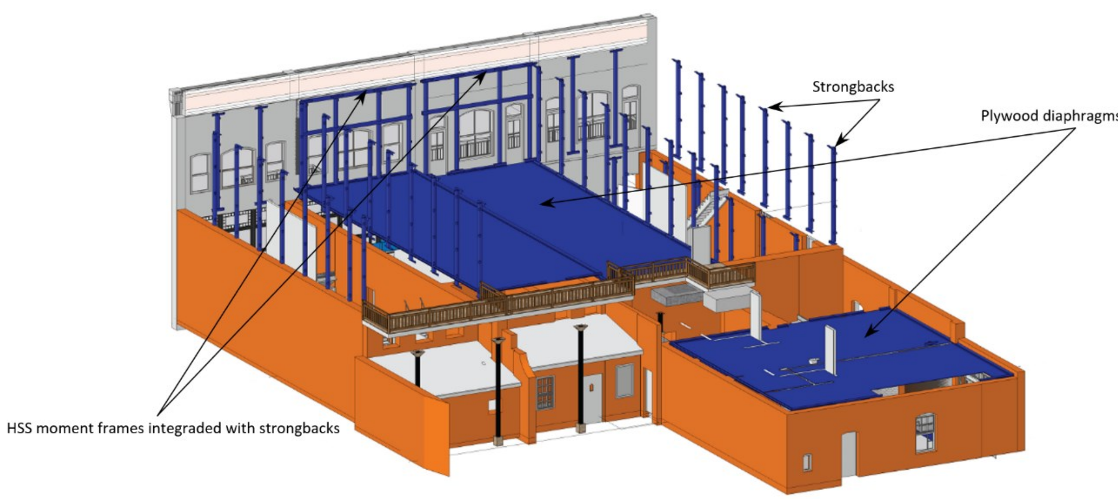



Figure 3.18, Structural seismic upgrade solution by adding HSS strongbacks, moment frames and plywood sheathings, south-west view

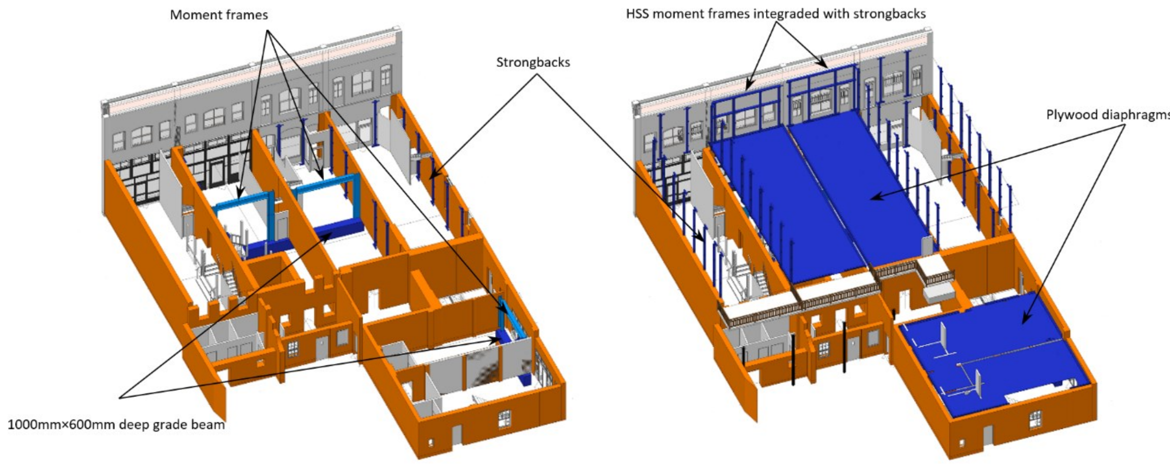



Figure 3.19, a) Layout of HSS strongbacks and moment frames at level 1; b) Layout of HSS strongbacks, moment frames and plywood sheathings at level 2

## 3.9. Expenses Summary and Payback Period

The costs of energy and seismic upgrades were shown in detail in the previous sections. These costs are based on the construction fees in Vancouver, BC, Canada and in Canadian dollars. These costs were calculated based on the *Yardsticks for Costing; Cost Data for the Canadian Construction Industry 2019* [50]. Although construction cost estimate is a function of time, it is expected that these price lists would remain constant until the end of 2020. Table 3.13 presents a summary of all the applied energy and seismic retrofit prices based on square meters ($m^2$) and square feet ($ft^2$).

Table 3.13, Summary of all retrofit option costs

| Type of Retrofitting Action | Description of Req. Area | Req. Area m² | Cost/m² | Cost/ft² |
|---|---|---|---|---|
| Seismic Retrofit | Total floor area | 1321 | \$53.6 | \$5.0 |
| Energy Retrofit, Exterior Walls; solution 1 | Total areas of external walls | 414.04 | \$156 | \$14.5 |
| Energy Retrofit, Exterior Walls; solution 2 | Total areas of external walls | 414.04 | \$26.5 | \$2.45 |
| Energy Retrofit, Exterior Walls; solution 3 | Total areas of external walls | 414.04 | \$30 | \$2.8 |

| Type of Retrofitting Action | Description of Req. Area | Req. Area m² | Cost/m² | Cost/ft² |
|---|---|---|---|---|
| Energy Retrofit, Exterior Walls; solution 4 | Total areas of external walls | 414.04 | $85 | $7.9 |
| Energy Retrofit, Exterior Walls; solution 5 | Total areas of external walls | 414.04 | $100.5 | $9.3 |
| Energy Retrofit, First Floor | Area of store #543 | 85.95 | $31 | $2.9 |
| Energy Retrofit, Second Floor | Total area of 2nd floor | 544.34 | $174.5 | $16.2 |
| Energy Retrofit, Roof | Total area of roof | 544.17 | $47 | $4.4 |

*$: Canadian dollars*

In any cost-benefits analysis, it is very important to know that what the short-term and long-term benefits of integrating energy and seismic retrofits are. By calculating the annual energy costs for both before and after retrofitting, it is found that the integration of energy and seismic retrofitting of heritage buildings provides economic benefits to owners while improving carbon emissions and building safety. As shown by Equations 3.1 and 3.2, the annual energy cost ($E_{cost}$ ) of the building before retrofitting on the natural gas price basis (0.085 $/kWh) [59] is $66,825, this cost after retrofitting reduces to $17,390. That is an almost 75.5% or $49,435 reduction in energy consumptions per year.

Since the total cost of seismic and energy retrofitting is $215,454, it can be said that the payback period (PBP) for these upgrades is less than five years, this can be calculated by Equation 3.3. If only energy retrofitting was considered, at a cost of $144,654, the payback period would be 3 years. That is based on reducing energy consumption of the building without increasing the safety level.

Therefore, integrating energy and seismic retrofits delivers payback with safety. As immediate benefits, energy upgrades reduce the energy consumption and carbon emissions of the building. Besides, as long-term benefits, seismic upgrades improve the structural resistance of the building; consequently, occupants' safety is increased as well. Meanwhile, separate seismic and energy retrofit adds $24,454 more to the project's costs. This additional cost is related to plywood sheathing which is an important component for both energy and seismic retrofitting. Figure 3.20 shows the cost differences in doing separate and simultaneous seismic and energy retrofitting.

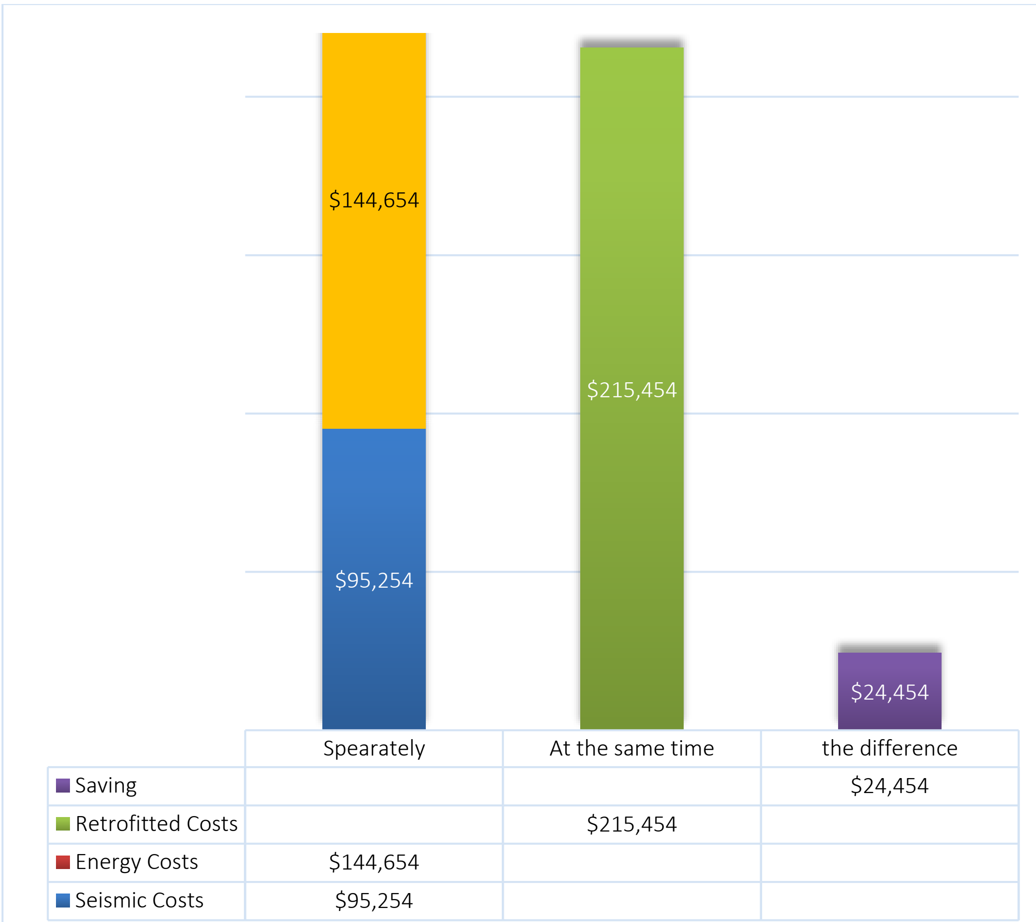



Figure 3.20, Comparison between costs of separate and simultaneous seismic and energy retrofit

# Chapter 4
# Conclusion and Future Work
## 4.1. Conclusion

1. This study showed that simultaneous energy and seismic retrofitting of historic buildings, aimed at lowering energy demand and greenhouse emissions, is possible and economically feasible. In this case study, five energy retrofitting options were introduced and compared with the initial conditions based on the amount of annual heating demand per square meter and cost-benefit analysis of options. In accordance with PHPP outputs, in general, at least a 50% reduction in heating demand and energy consumption is attainable.

2. Since the energy demand in all five actions was closed, from 137.6 to 155 kWh/m$^2$y, cost estimation highlighted that it is possible to reach a reasonable efficiency with the minimum expenses.

3. Option two was considered as the best energy retrofit solution for exterior walls by reducing more than 450 kWh/m$^2$y (almost 75% reduction in annual heating demand per square meter) and the total price of $10,935 , which is equal to $26.5 per square meter. Expenses for energy retrofitting of the first floor, second floor, and roof are $31 per square meter, $174.4 per square meter, $47 per square meter respectively. Also, by spending only $8.86 per square meter in insulating and air-tightening for floors and roof assemblies, a 40% reduction in annual energy demand would be obtained.

4. Considering doing energy and seismic retrofit at the same time is less expensive than doing each of them separately. In this study, separate seismic and energy retrofit needs $24,454 more; while doing both at the same time means 11% cost savings.
5. The total project costs would be $215,454 and based on $49,435 saved from annual energy consumption, the payback period for these upgrades would be less than five years.
6. The seismic solutions for this case study with its heritage value improved the diaphragm capacity of the floors and roofs and strengthened the connections of the URM walls by adding plywood sheathings, shear walls, strong backs, and moment frames attached into deep grade concrete beams.
7. This study showed that comparison of the amount of saved energy, R-Values, annual heating demand and estimated cost of various retrofitting solutions would be a reliable method to select the best solution for energy and seismic retrofitting.

# 4.2. Future Work

## 4.2.1. Moisture Design

For future of this project, the proposed options can be compared with a moisture management design tool. This helps to have a better understanding for choosing a more accurate solution for retrofitting of the building. In addition to account for heating demand, R-Values and cost-benefit of each option, it is important to understand the effects of humidity and mold growth conditions. Moisture conditions represent a widespread issue and have direct impacts on the health of occupants, service life and the aesthetic of building [60], [61].

One of the most comprehensive design tools with moisture transfer simulations is WUFI that considers both the hygrothermal conditions in a building component and the interior climate [62]. For example, in this software, it is possible to observe and control the total water content of a building component and compare it to the allowable to apply an intentional water/air leak on one layer in an assembly to observe the future activity of this infiltration. It is also possible to check the risk of condensation on the interior side of the components by comparing dew point temperature with room temperature.

### 4.2.2. Carbon Footprint Assessment

Since reducing greenhouse gases has always been one of the main concerns of the author and this research, another step that can help to meet CleanBC goals is comparing greenhouse gas emissions of various retrofit options. Using 2007 as the baseline, B.C. is committed though legislation to reductions of 40% by 2030. However, carbon emissions in B.C. in 2017 show a drop of two per cent over 10 years occurred [63]. These statistics show that to reduce greenhouse gas emissions and fossil fuels consumption in B.C. more efforts are needed.

Hence, greenhouse gas emissions assessment of different retrofit options will be another crucial task that will be calculated with ATHENA Impact Estimator in future work. It is very important to know that "A carbon footprint is the total greenhouse gas (GHG) emissions caused directly and indirectly by an individual, organization, event or product” [64].

# Bibliography

[1] T. B. of C. Secretariat and T. B. of C. Secretariat, "Survey of Commercial and Institutional Energy Use (SCIEU) - Buildings 2009 – Data Tables - Open Government Portal." https://open.canada.ca/data/en/dataset/e8c5aaf6-1275-46bb-9862-ce0f85ee4b83.

[2] "Heritage Register Apr 2020.pdf." Accessed: Jun. 20, 2020. [Online]. Available: https://www.victoria.ca/assets/City~Hall/Committees/Other~Committees/Heritage~Advisory~Panel/Heritage%20Register%20Apr%202020.pdf.

[3] "Earthquake Readiness," *https://www.victoria.ca*. https://www.victoria.ca/EN/main/residents/public-safety/emergency-preparedness/earthquake-readiness.html.

[4] M. of Environment, "Climate Planning & Action - Province of British Columbia." https://www2.gov.bc.ca/gov/content/environment/climate-change/planning-and-action.

[5] N. R. C. Government of Canada, "Residential Sector – Canada," Apr. 01, 2005. https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends_res_ca.cfm.

[6] B. Dionysios, "Innovative Materials for Seismic and Energy Retrofitting of the Existing EU Buildings," *EU Science Hub - European Commission*, Jan. 16, 2018. https://ec.europa.eu/jrc/en/publication/innovative-materials-seismic-and-energy-retrofitting-existing-eu-buildings.

[7] B. Dong, C. Kennedy, and K. Pressnail, "Comparing life cycle implications of building retrofit and replacement options," *Can. J. Civ. Eng.*, Feb. 2011, doi: 10.1139/l05-061.

[8] T. K. Efthimiadoua, Th. N. Nikolaidisa, and C. C. Baniotopoulos, "A Sustainable Design Strategy for the Restoration of Historical Buildings," *Procedia Environ. Sci.*, vol. 38, pp. 234–241, Jan. 2017, doi: 10.1016/j.proenv.2017.03.110.

[9] M. Rabani, H. B.Madessa, and N. Nord, "A state-of-art review of retrofit interventions in buildings towards nearly zero energy level," *Energy Procedia*, vol. 134, pp. 317–326, Oct. 2017, doi: 10.1016/j.egypro.2017.09.534.

[10] M. Beccali, M. Cellura, M. Fontana, S. Longo, and M. Mistretta, "Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits," *Renew. Sustain. Energy Rev.*, vol. 27, no. C, pp. 283–293, 2013.

[11] Z. Ma, P. Cooper, D. Daly, and L. Ledo, “Existing building retrofits: Methodology and state-of-the-art,” *Energy Build.*, vol. 55, pp. 889–902, Dec. 2012, doi: 10.1016/j.enbuild.2012.08.018.

[12] M. Lešnik, M. Premrov, and V. Žegarac Leskovar, “Design parameters of the timber-glass upgrade module and the existing building: Impact on the energy-efficient refurbishment process,” *Energy*, vol. 162, pp. 1125–1138, Nov. 2018, doi: 10.1016/j.energy.2018.08.108.

[13] F. Ascione, F. Rossi, and G. PeterVanoli, “Energy retrofit of historical buildings: theoretical and experimental investigations for the modelling of reliable performance scenarios,” *Energy Build.*, vol. 43, no. 8, pp. 1925–1936, Aug. 2011, doi: 10.1016/j.enbuild.2011.03.040.

[14] A. Charles, W. Maref, and C. M. Ouellet-Plamondon, “Case study of the upgrade of an existing office building for low energy consumption and low carbon emissions,” *Energy Build.*, vol. 183, pp. 151–160, Jan. 2019, doi: 10.1016/j.enbuild.2018.10.008.

[15] N. Casquero-Modrego and M. Goñi-Modrego, “Energy retrofit of an existing affordable building envelope in Spain, case study,” *Sustain. Cities Soc.*, vol. 44, pp. 395–405, Jan. 2019, doi: 10.1016/j.scs.2018.09.034.

[16] P. Institute, “Evolution of Energy Efficiency Requirements in the B.C. Building Code,” *Pembina Institute*. https://www.pembina.org/pub/evolution-of-energy-efficiency-requirements-in-the-bc-building-code (accessed Jun. 20, 2020).

[17] S. Limoncu and B. Celebioglu, “Strengthening of Historic Buildings in Post-Disaster Cases,” 2007. /paper/Strengthening-of-Historic-Buildings-in-Cases-Limoncu-Celebioglu/2742632375d9d26b78822d2754a2e4f5a0d9defe.

[18] A. Cascardi, R. Dell’Anna, F. Micelli, F. Lionetto, M. A. Aiello, and A. Maffezzoli, “Reversible techniques for FRP-confinement of masonry columns,” *Constr. Build. Mater.*, vol. 225, pp. 415–428, Nov. 2019, doi: 10.1016/j.conbuildmat.2019.07.124.

[19] “Recommendations for the analysis, conservation and structural restoration of architectural heritage.” ICOMOS/ISCARSAH Committee, 2005, [Online]. Available: www. icomos.org.

[20] W.-S. Chang, “Repair and reinforcement of timber columns and shear walls – A review,” *Constr. Build. Mater.*, vol. 97, pp. 14–24, Oct. 2015, doi: 10.1016/j.conbuildmat.2015.07.002.

[21] M. E. Sarafraz and F. Danesh, “New technique for flexural strengthening of RC columns with NSM FRP bars,” *Mag. Concr. Res.*, May 2015, doi: 10.1680/macr.10.00139.

[22] A. Seifi, A. Hosseini, M. Mohammad Sadegh, and Z. Mohammad Sajjad, "Improving seismic performance of old-type RC frames using NSM technique and FRP jackets," *Eng. Struct.*, vol. 147, pp. 705–723, Sep. 2017, doi: 10.1016/j.engstruct.2017.06.034.

[23] P. Prabhakaran and G. Joseph, "Shear Performance of Embedded Through Section (ETS) Over Near Surface Mounting (NSM) Method of RC Beams," in *Proceedings of SECON'19*, May 2019, pp. 919–933, doi: 10.1007/978-3-030-26365-2_84.

[24] E. Poletti, G. Vasconcelos, and M. Jorge, "Application of near surface mounted (NSM) strengthening technique to traditional timber frame walls," *Constr. Build. Mater.*, vol. 76, pp. 34–50, Feb. 2015, doi: 10.1016/j.conbuildmat.2014.11.022.

[25] E. Poletti, G. Vasconcelos, J. M.Branco, and A. M.Koukouviki, "Performance evaluation of traditional timber joints under cyclic loading and their influence on the seismic response of timber frame structures," *Constr. Build. Mater.*, vol. 127, pp. 321–334, Nov. 2016, doi: 10.1016/j.conbuildmat.2016.09.122.

[26] M. Kobraei and M. Z. Jumaat, "Using FRP-bars in Concrete Beams: A General Review," presented at the TECHPOS 2009, Kuala Lumour, Malaysia, 2009, doi: 10.1109/TECHPOS.2009.5412041.

[27] M. Kobraei, M. Z. Jumaat, and P. Shafigh, "An experimental study on shear reinforcement in RC beams using CFRP-bars," *Sci. Res. Essays*, vol. 6, no. 16, pp. 3447–3460, Aug. 2011, doi: 10.5897/SRE11.650.

[28] G. Maddaloni, M. D. Ludovico, A. Balsamo, G. Maddaloni, and A. Prota, "Dynamic assessment of innovative retrofit techniques for masonry buildings," *Compos. Part B Eng.*, vol. 147, pp. 147–161, Aug. 2018, doi: 10.1016/j.compositesb.2018.04.038.

[29] A. Younis and U. A Ebead, "A study on the bond behavior of different FRCM systems," presented at the MATEC Web of Conferences, 2018, doi: 10.1051/matecconf/201819909003.

[30] C. Michel, A. Karbassi, and P. Lestuzzi, "Evaluation of the seismic retrofitting of an unreinforced masonry building using numerical modeling and ambient vibration measurements," *Eng. Struct.*, vol. 158, pp. 124–135, Mar. 2018, doi: 10.1016/j.engstruct.2017.12.016.

[31] P. B. Lourenço, N. Mendes, L. F. Ramos, and D. V. Oliveira, "Analysis of Masonry Structures Without Box Behavior," *Int. J. Archit. Herit.*, Jun. 2011, Accessed: Jul. 20, 2020. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/15583058.2010.528824.

[32] A. Gubana and M. Melotto, “Experimental tests on wood-based in-plane strengthening solutions for the seismic retrofit of traditional timber floors,” *Constr. Build. Mater.*, vol. 191, pp. 290–299, Dec. 2018, doi: 10.1016/j.conbuildmat.2018.09.177.

[33] F. Cote, R. Biagi, H. Bart-Smith, and V. S. Deshpande, “Structural response of pyramidal core sandwich columns,” *Int. J. Solids Struct.*, vol. 44, no. 10, pp. 3533–3556, May 2007, doi: 10.1016/j.ijsolstr.2006.10.004.

[34] X. Zhao, H. Liang, Y. Lu, and P. Zhao, “Size effect of square steel tube and sandwiched concrete jacketed circular RC columns under axial compression,” *J. Constr. Steel Res.*, vol. 166, p. 105912, Mar. 2020, doi: 10.1016/j.jcsr.2019.105912.

[35] L.-L. Chung, Y.-S. Yang, K.-H. Lien, and L.-Y. Wu, “In situ experiment on retrofit of school buildings by adding sandwich columns to partition brick walls,” *Earthq. Eng. Struct. Dyn.*, vol. 43, no. 3, pp. 339–355, Mar. 2014, doi: 10.1002/eqe.2347.

[36] S. Soyoz *et al.*, “Ambient and Forced Vibration Testing of a Reinforced Concrete Building before and after Its Seismic Retrofitting,” *J. Struct. Eng.*, vol. 139, no. 10, pp. 1741–1752, Oct. 2013, doi: 10.1061/(ASCE)ST.1943-541X.0000568.

[37] U. Hancilar, E. Çaktı, and M. Erdik, “Earthquake performance assessment and rehabilitation of two historical unreinforced masonry buildings,” *Bull. Earthq. Eng.*, vol. 10, no. 1, pp. 307–330, Feb. 2012, doi: 10.1007/s10518-011-9281-3.

[38] M. A. ElGawady, P. Lestuzzi, and M. Badoux, “In-Plane Seismic Response of URM Walls Upgraded with FRP,” *J. Compos. Constr.*, vol. 9, no. 6, pp. 524–535, Dec. 2005, doi: 10.1061/(ASCE)1090-0268(2005)9:6(524).

[39] M. A.ElGawady, P. Lestuzzi, and M. Badoux, “A seismic retrofitting of unreinforced masonry walls using FRP,” *Compos. Part B Eng.*, vol. 37, no. 2–3, pp. 148–162, Apr. 2005, doi: 10.1016/j.compositesb.2005.06.003.

[40] M. A. ElGawady, P. Lestuzzi, and M. Badoux, “A Review of Conventional Seismic Retrofitting Techniques for URM,” presented at the Proceedings of 13th International Brick/Block Masonry Conference, 2004, [Online]. Available: https://infoscience.epfl.ch/record/105146.

[41] J. Sherstobitoff, G. Taylor, and J. Shuttleworth, “Seismic retrofit strategies for historical clay brick masonry school buildings; British Columbia, Canada,” 2010, vol. 2, pp. 988–997.

[42] A. Kuwahara, K. Tanaka, M. Inoue, and Y. Hiraoka, “Damage report of wooden buildings in mashiki town caused by the 2016 Kumamoto Earthquake,” presented at the WCTE 2018 - World Conference on Timber Engineering, 2018.

[43] N. Ruggieri, G. Tampone, and R. Zinno, "Typical Failures, Seismic Behavior and Safety of the 'Bourbon System' with Timber Framing," *Advanced Materials Research*, 2013. /AMR.778.58.

[44] A. Khaloo, A. Khoshnevis, and M. Yekrangnia, "On the vulnerability of the Shrine of Prophet Daniel through field observation and numerical simulation," *Eng. Fail. Anal.*, vol. 102, pp. 237–259, Aug. 2019, doi: 10.1016/j.engfailanal.2019.04.033.

[45] L. Pinto, "Inventory of repair and strengthening methods timber," 2008. /paper/Inventory-of-repair-and-strengthening-methods-Pinto/dff40d84d474263efcb946dcdc81c750d31d0ca3.

[46] T. Georgios, A. Roberta, and T. Fabio, "Seismic strengthening of RC buildings," 2014, doi: 10.2788/138156.

[47] A. Dandurand, "Seismic upgrading of existing structures." McGill University, 1988.

[48] "Fan Tan Alley," *Tourism Victoria*, Jun. 27, 2017. https://www.tourismvictoria.com/see-do/activities-attractions/attractions/fan-tan-alley (accessed Jul. 23, 2020).

[49] A. Peel, *PHPP - Typical material thermal resistance values (Excel Sheet)*. Passive House Institute (PHI), 2015.

[50] "Yardsticks for Costing; Cost Data for the Canadian Construction Industry 2019," 2019. www.rsmeans.com.

[51] *Passive House Planning Package*. Passive House Institute, 2015.

[52] *Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard*. Passive House Institute, 2015.

[53] *BC Fire Code 2012*. British Columbia Codes, 2012.

[54] *BC Plumbing Code 2012*. British Columbia Codes, 2012.

[55] *BC Building Code 2012*. British Columbia Codes, 2012.

[56] *Seismic evaluation and retrofit of existing buildings*. American Society of Civil Engineers, 2017.

[57] D. E. Allen, J. H. Rainer, and A. M. Jablonski, *Guidelines for seismic evaluation of existing buildings*. Government of Canada National Research Council, 1993.

[58] "Committee of the Whole - February 22, 2018," *City of Victora*, 2018. https://pub-victoria.escribemeetings.com/filestream.ashx?DocumentId=20133.

[59] "Electricity Prices in Canada (Updated 2020)," *energyhub.org*, Feb. 14, 2020. https://www.energyhub.org/electricity-prices/ (accessed Jul. 25, 2020).

[60] S. Yu, S. Zheng, K. Li, and G. Feng, "The research of the mold growth conditions in different climate zone," in *Ventilation 2015 - Proceedings of the 11th International Conference on Industrial Ventilation*, 2015, vol. 1, pp. 146–154.

[61] S. Fantucci, F. Isaia, V. Serra, and M. Duttob, "Insulating coat to prevent mold growth in thermal bridges," *Energy Procedia*, vol. 134, pp. 414–422, Oct. 2017, doi: 10.1016/j.egypro.2017.09.591.

[62] "What is WUFI®? | WUFI (en)." https://wufi.de/en/software/what-is-wufi/.

[63] M. of Environment, "Provincial Greenhouse Gas Emissions Inventory - Province of British Columbia." https://www2.gov.bc.ca/gov/content/environment/climate-change/data/provincial-inventory (accessed Jul. 25, 2020).

[64] "Carbon footprinting guide," *https://www.carbontrust.com/resources/carbon-footprinting-guide*, Jan. 14, 2020. https://www.carbontrust.com/resources/carbon-footprinting-guide.