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Cost and Benefit of New Buildings Designed to Enhanced Post-Earthquake Performance Levels

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ABSTRACT

Most new buildings are designed for earthquake loads as Normal Importance buildings as defined by the National Building Code of Canada (NBC). The performance of such buildings is typically described as "life safety/collapse prevention".

BC Housing initiated a study to assess the costs and benefits of designing new buildings to one of three different enhanced performance levels with respect to the code level earthquake. These alternate performance levels are: 1) per Post-disaster Importance requirements in NBC, 2) a "refuge" level to provide undamaged structural performance on the lowest floor of the building and repairable structural performance on the upper floors, and 3) an "operational" level to provide undamaged structural performance for the entire building. The "refuge" and "operational" levels also have specific performance criteria for mechanical, electrical, and architectural components of the building.

The study was carried out for seven existing BC Housing buildings in the Vancouver area and southern Vancouver Island – regions of high seismicity. A variety of buildings with different construction materials, shapes, and heights were selected to capture a representative cross-section of buildings. The study relied on existing construction drawings and related actual construction costs. This unique study provides valuable data on the costs to achieve enhanced performance, with listed benefits to occupants in regards to operability of defined building components. This paper presents the methodology utilized in the study, a representative summary of each building type assessed, details of the "refuge" and "operational" performance levels, modifications to the structural system and non-structural components required to meet the three performance levels, and the incremental costs to achieve the enhanced performance levels. The study's outcome will be considered by BC Housing for possible modifications to their new building design standards and provides reference material for possible changes in NBC regarding enhanced performance for some new buildings.

Keywords: enhanced performance, new buildings, code changes, cost vs benefit.

INTRODUCTION

BC Housing design guidelines currently specify their new buildings to be designed as "Normal" Importance buildings per building code requirements. This design is intended to achieve a "life-safety" or "collapse prevention" level of performance for the code design level earthquake, to enable occupants to safely exit the building. However, the damage of the building may be extensive and not repairable, or if repairable the occupants may not be able to re-enter or use the building for some significant/undefined length of time. This performance is representative of all new buildings designed as Normal Importance, regardless of the client/owner.

This paper presents a study of the cost effects and related benefits of designing future new buildings to higher seismic performance levels than that per current and previous designs to code Normal Importance requirements. Three increasingly higher-performance design levels were defined: "Post-disaster" per building code, and "Refuge" and "Operational". These levels are defined with the intent of reducing the damage to newly designed and constructed buildings in the event of an earthquake, with the performance objectives varying from reduced but still undefined damage (Post-disaster per code), to effectively undamaged and immediately functional for a lower level 'common area' of the building, with code post-disaster design for upper levels (Refuge), to effectively undamaged and immediately functional for the entire building (Operational).

Seven existing BC Housing residential buildings or developments originally designed according to the building code as "Normal" importance buildings were assessed and high level "re-designs" carried out for the three higher performance levels. This study was based on available drawings provided by BC Housing; no site visits were carried out.

PERFORMANCE LEVELS OBJECTIVES

Earthquake Hazard

The earthquake hazard is based on three different types of earthquakes that can occur in BC: subduction earthquakes with suggested Magnitude 9, with long duration, and a known fault line; shallow crustal earthquakes with Magnitudes in the 7's, with short duration, and locations 'unpredictable'; and deeper subcrustal earthquakes with Magnitudes up to the high 7's, with short duration, with only some locations known and other locations 'unpredictable'.

New buildings in BC are designed for this hazard per requirements in the current BC Building Code (BCBC) (previous edition 2012, with newest edition issued December 10, 2018) which is based on the National Building Code of Canada (NBC) (2010 version for BCBC 2012 and 2015 version for BCBC 2018). Buildings in Vancouver are designed per the Vancouver Building By-Law which is usually consistent with the current BCBC. The code level design earthquakes in these codes have an annual exceedance probability (AEP) of 1/2475; also referred to as 2% probability of exceedance in 50 years.

The design of new buildings per code achieves a code specified minimum performance level if any of the three types of earthquakes occur; the performance level is discussed further in the next section. Furthermore, the codes specify the connection (restraint) forces for a variety of non-structural elements, components, and equipment within a building. Some of the existing buildings in this study were designed to earlier versions of the code; the seismic design data and design requirements typically vary between each version of the codes. The focus of recommendations in this study for 'performance based' design of new buildings is with reference to seismic design data and design requirements per NBC 2015/BCBC 2018 and related CSA material standards.

Four Performance Levels

The reference performance level and three enhanced performance levels defined in this study are described below.

Code – Normal: The reference and minimum level of performance for buildings designed by code with the Importance Factor I_E = 1.0; life safety/collapse prevention performance level.

Code – Post-disaster: An enhanced level of performance to Code – Normal, for buildings designed by code with the Importance Factor I_E = 1.5; a 'force based' design to reduce damage compared to that of a Code-Normal design. However, fully operational performance is not guaranteed, and the level of performance can vary.

Refuge: A specified performance condition for this study, with 'operational' performance in a designated "common area" (such as basement and ground floor), with Code – Post-disaster performance elsewhere. Thus, this performance level is enhanced from Code – Post-disaster for the common area, and same as Post-disaster elsewhere.

Operational: A specified performance condition for this study, with 'operational' performance for the entire building and services within the property. Thus, enhanced from Code – Post-disaster and enhanced from Refuge.

These performance levels are illustrated graphically in Figure 1 below. The shading using green, yellow and red, is intended to illustrate which type of post-earthquake inspection 'tagging' the building is likely to have after the code design level earthquake. Those with hatched shading are intended to convey that the performance level, extent of damage, and type of 'tagging' may vary.

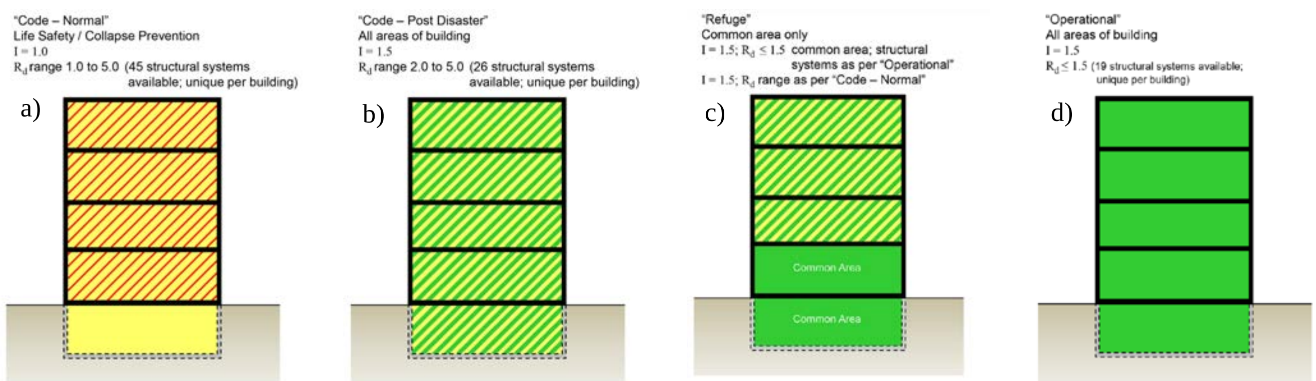

Figure 1. Performance levels: a) Code- Normal, b) Code-Post Disaster, c) Refuge, d) Operational.

Table 1 outlines the performance conditions of a selection of components and aspects of a building, for each of the four performance levels noted above.

Table 1. Selection of Performance Levels Outline.

Designation	**"Code – Normal"**	**"Code – Post Disaster"**	**"Refuge"**	**"Operational"**
Building Area Designed to Post-EQ Operational Standards	None	Whole Building to Code Level, but may or may not be Operational	Main Floor & Basement Only (Common Area)	Whole Building
Code Design	I = 1.0 and any Rd	I = 1.5 and Rd ≥ 2.0	I = 1.5 and Rd ≤ 1.5 Common Area only and Rd* Elsewhere	I = 1.5 and Rd ≤ 1.5
Occupancy Objective – Post Earthquake	Life safety, but no guarantee of occupancy. Entire building can be safely evacuated (i.e. does not collapse on occupants).	Damage control, but no guarantee of being operational. Entire building should remain occupiable but will require inspections to confirm such.	A designated refuge area of the building (e.g. common lounge on first or ground floor, or parkade where climate permits) can be used as group lodging. The upper floors may not be immediately habitable; occupants move to designated refuge area post-earthquake. No displacement of occupants away from the building.	Building and suites within it can be occupied with no interruption. No occupants are displaced.
Structural Repair or Demolition Required	Repairs are anticipated and may be extensive. Demolition may be required.	Repairs are anticipated. Extent of repairs not defined; will vary based on structural systems selected.	Only minor repairs necessary to finishing anticipated for designated refuge area. Significant structural repairs and services anticipated for the upper floors and all suites. Demolition is not required.	Only minor repairs necessary to finishing. No structural repair or demolition is required.
HVAC Services	Functionality may not be available. May require repair or replacement. Equipment should remain restrained, if element it is connected to remains structurally sound.	Functionality may be available. May require repair. Equipment should remain restrained.	Regular or alternate HVAC in designated refuge area to remain operational. HVAC on upper floors and suites may not be operational and may require repair. Add standalone propane storage tank and piping. Convert heating boiler, kitchen range and fireplace to dual fired (propane).	Within the building, no repair is required to supply HVAC if lifeline services are operational. Add standalone propane storage tank and piping. Convert heating boiler, kitchen range and fireplace to dual fired (propane). Provide stand-by pumps for back-up heating and domestic water circulation.
Pipes, Ducts, Cable Trays, and Conduits Within Building	Equipment should remain restrained, if element it is connected to remains structurally sound.	Equipment should remain restrained.	Equipment to remain fully restrained in refuge area. Will enable services to continue in refuge area.	Equipment to remain fully restrained. Will enable services to continue.
Ceilings, Lights, and Other Ceiling Attachments	Items should remain restrained, if element it is connected to remains structurally sound.	Items should remain restrained.	Equipment to remain fully restrained in refuge area. Will enable services to continue in refuge area; in rest of building.	Equipment to remain fully restrained in refuge area. Will enable services to continue in refuge area; in rest of building.

In Figure 1 and Table 1, Rd is a "ductility related force modification factor" used in building design. The current NBC 2015 / BCBC 2018 has 45 different structural systems for building design, each with a specific Rd value that varies from 1.0 to 5.0. Design with an Rd=1.0 will result in elastic (no damage) performance of the structure but the cost will be high due to the high force levels designed for. Comparatively, design with an Rd=5.0 will result in 'controlled damage' to dissipate the earthquakes energy and likely permanent residual drift; the cost will be much lower as the force levels are approximately 1/5 of that for an Rd=1.0 design. Thus, the trade-off of reduced cost versus increased ductility (damage).

In Figure 1 and Table 1, I_E is the code Importance Factor, with a value of 1.0 for Normal buildings such as those typically designed/built by BC Housing and considered in this study, and with a value of 1.5 for Post-disaster buildings. Design using the higher I_E value will result in less damage for the design earthquake. Furthermore, for Post-disaster buildings, the code has other specific requirements limiting interstorey drift to 1% (compared to 2.5% for Normal buildings) and limiting the types of irregularities that can exist (i.e. requiring a 'more regular' building for Post-disaster buildings).

METHODOLOGY

Structural Evaluation

In this study, the assessment and evaluation of the structural system does not involve a comprehensive analysis or computer modelling of the building. The analysis is based on reasonable structural engineering manual calculations to determine the capacity of the existing Seismic Force Resisting System (SFRS) required to achieve the desired performance level.

For each building evaluated, the original design criteria was gathered from the existing structural drawings which includes but is not limited to seismic design data and the SFRS used in the building. The analysis was then performed for the seismic demand based on the NBC and only related to the SFRS used in the building. Existing architectural drawings were used to verify any dimensions and details not shown on the structural drawings.

Evaluation of the structural configuration of the SFRS was performed first to determine if there are any structural irregularities that needed to be taken into account. The existing layouts of the buildings, which originally were not designed for more than 'normal' code performance, have some irregularities not allowed for higher performance levels; however, to limit any floor reconfigurations some irregularities remained after redesign for the purposes of this study. This step was not intended to be thorough, but adequate to determine the distribution of the seismic forces to the SFRS. The method of analysis was carried out as per the British Columbia Building Code (BCBC) applicable at the time of the original design with consideration of the SFRS type used in the building. For most of the low-rise buildings, the 'equivalent static force' procedure is appropriate to determine the seismic demand. The capacity of the SFRS used in the building is calculated using the applicable material CSA standard (wood, masonry, concrete, or steel). For the mid-rise concrete buildings, a response spectrum analysis was performed using ETABS [3] computer program.

The analysis considered the two primary orthogonal directions of loading (such as North-South and East-West), unless an irregular shape required otherwise. The roof and floor diaphragms (timber or metal deck) were assessed as ductile elements able to yield and dissipate energy, while the chords, drag struts, and collector elements were sized based on the overall capacity of the diaphragm.

For the Code – Post-disaster buildings, the Importance factor is set to 1.5 and the interstorey drift is limited to 1% of floor to floor height. This increases the seismic force demands at each floor levels.

For the Common Area of the Refuge performance buildings, the designated common area which is mainly the main floor level will have an Importance factor of 1.5 and the ductility factor (Rd) of the SFRS less than or equal to 1.5. This will significantly increase the seismic demand forces due to the very low ductility that is required for the system at the main floor level. It will require all of the SFRS at that level to remain nearly elastic. For post-disaster requirements the minimum ductility requirement (Rd) should be 2.0 or larger. At the other areas (all above the main floor level), the post-disaster requirements as described above will apply.

For the Operational performance buildings, the entire floor level will be designed to have an Importance factor of 1.5 and very low ductility level (Rd) of less than or equal to 1.5. The increase of the seismic demand forces are now applicable to each floor level and requires the overall SFRS systems to behave nearly elastic.

Mechanical, Electrical, Architectural and Non-structural Components

The proposed performance for mechanical and electrical equipment, and the seismic restraints for mechanical, electrical, architectural, and other non-structural components for the different performance levels are listed in Table 1.

For the Code – Normal buildings, the minimum code requirement is seismic restraint of such components, with some detailed requirements for glazing per NBC 2015. For the Code – Post-disaster buildings, the minimum code requirements is as per Code – Normal, but with increased restraint forces and more stringent requirements for glazing. For the Common Area of the Refuge performance buildings and the entire area of the Operational performance buildings, the intent is to have all components operational if services from the outside infrastructure are available to the building site, and a lesser extent of operation based on power limitations from a standby generator on-site and from other enhancements incorporated into the building/site.

The intent of this study is to estimate the incremental cost to the Code – Normal building for all these components, for the stated three enhanced performance levels.

Cost Estimates

For the structural SFRS a material quantity take-off was carried out. The quantity is based on each element of the SFRS required in the building for the applicable performance level. The scope of the estimation is limited to the SFRS systems being used (lateral load resisting system, hold down anchors, diaphragms, drag struts/collectors, foundations). For the mechanical and electrical aspects, an order of magnitude estimate of the incremental costs is currently being developed (not available at time of paper submission). The main objective of the cost estimate is to gain an understanding of the incremental costs of each of the enhanced performance levels relative to the Code – Normal building.

REPRESENTATIVE BUILDINGS

Wood Frame Low Rise Building – Greater Vancouver Area

Figure 2. Wood frame low rise building rendering.

Structural Components

The building consists of four storeys above-grade, of which the upper three floors are of conventional wood-frame construction with reinforced concrete structure forming the main floor.

The equivalent static force method is used to calculate the seismic forces, as permitted by the NBC. The NBC prescribes a method of redistributing the seismic weight of the lower floors to the upper floors to reflect the deformation of the structure under seismic loading. However, the first storey lateral stiffness of the concrete structure is relatively high compare to the wood-frame above, thus the two systems were de-coupled and analyzed separately, with the wood structure assumed fixed at the concrete slab.

Refer to Table 2 and Table 3 for the modifications required for the target performance levels of “Refugee” and “Operational.

Table 2. Performance Objective: Refugee – Common Area Only.

Modifications Required (North-South and East-West Direction Loading)		
Level	**SRFS**	**Diaphragm**
Penthouse	Continuous Tie Rods Hold Downs	No modification required
Roof to 4th Floor	Increase nail spacing Continuous Tie Rods Hold Downs	No modification required
4th Floor to 3rd Floor	Increase nail spacing Thicker plywood sheathing Continuous Tie Rods Hold Downs	No modification required
3rd Floor to 2nd Floor	Plywood sheathing both sides Thicker plywood sheathing Continuous Tie Rods Hold Downs	No modification required
2nd Floor to Main Floor	No modification required	No modification required
Foundations	No modification required	No modification required

Table 3. Performance Objective: Operational – All Areas of the Building.

Modifications Required (North-South and East-West Direction Loading)		
Level	**SRFS**	**Diaphragm**
Penthouse	Continuous Tie Rods Hold Downs	No modification required
Roof to 4th Floor	Increase nail spacing Continuous Tie Rods Hold Downs	No modification required
4th Floor to 2nd Floor	Increase nail spacing Plywood sheathing both sides Continuous Tie Rods Hold Downs Steel posts required at end of shearwalls	No modification required
2nd Floor to Main Floor	No modification required	No modification required
Foundations	No modification required	No modification required

Figure 3 shows a floor plan of the building highlighting the nailed plywood shearwalls as the existing SFRS.

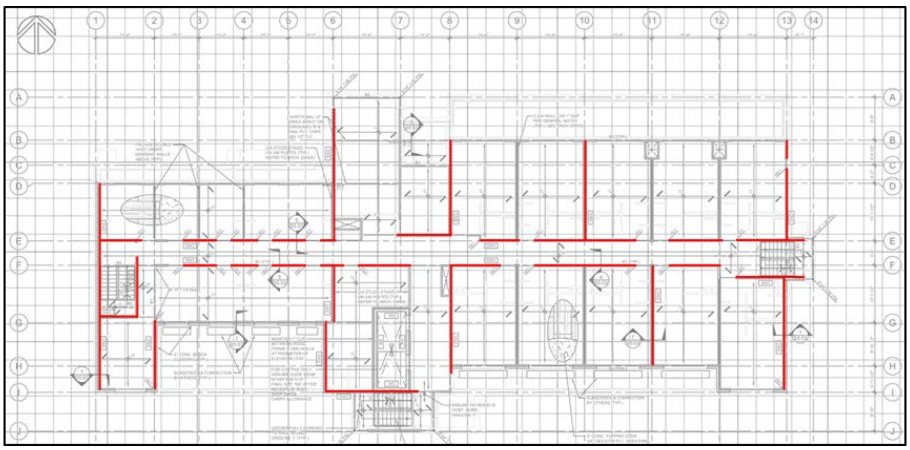

Figure 3. Typical upper floor plan of the building highlighting (in red) nailed plywood shearwalls as SFRS.

Architectural Non-Structural Components

For the purposes of this study, it is assumed that all components for the Code-Normal building are restrained per code requirements. For the Code Post-disaster building, an allowance of an incremental cost of $2.50/m^2$ is included for restraints for larger forces and some new code requirements for glazing. For the Refuge and Operation buildings, an allowance of an incremental cost of $4.50/m^2$ is included to meet the performance requirements per Table 1.

Incremental Cost Summary

Table 4 provides a summary of the incremental costs for the various performance levels ($ values rounded).

Table 4. Incremental Cost Estimate Summary.

Base Cost				**Gross Area**		
$9.8 M				**3,294 m²**		
Incremental Cost	**Post-Disaster**		**Refugee**		**Operational**	
Structural	0.2%	$18k	0.2%	$18k	0.6%	$58k
Architectural	0.1%	$8k	0.15%	$15k	0.15%	$15k
Mechanical	TBD	TBD	TBD	TBD	TBD	TBD
Electrical	TBD	TBD	TBD	TBD	TBD	TBD

Mid-Rise Concrete Building – Greater Vancouver Area

Figure 4. Mid-rise concrete building rendering.

Structural Components

This building consists of 12 above-ground storeys and two underground parking levels. The ground floor and second floor cover the full area of the building, while the upper floors have reduced areas featuring a concrete elevator core, a concrete stairwell, and a masonry stairwell. The building's structure is mainly of conventional concrete construction with concrete columns for gravity loads and concrete shearwalls for lateral loads.

ETABS was used to obtain the seismic demand loads for this building. This accounts for higher mode participation in the calculation of the lateral loading, as well as the load-sharing permitted by the rigid diaphragm. The assumption of cracking of the concrete components and subsequent stiffness reduction was included in the analysis parameters.

Refer to Table 5 and Table 6 for the modification required for the target performance levels of "Refugee" and "Operational.

Table 5. Performance Objective: Refugee – Common Area Only.

Modifications Required		
Level	**SRFS**	**Diaphragm**
Roof to 8th Floor	No modification required	No modification required
8th Floor to P2	Increase concrete shearwall thickness including reinforcing bars	No modification required
Foundations	No modification required	No modification required

Table 6. Performance Objective: Operational – All Areas of the Building; Modifications Required.

Modification Required (North-South & East-West Loading)		
Level	**SRFS**	**Diaphragm**
Roof to P2	Increase concrete shearwall thickness including reinforcing bars	No modification required
Foundations	No modification required	No modification required

Figure 5 shows a floor plan of the building highlighting the concrete shearwalls as the SFRS.

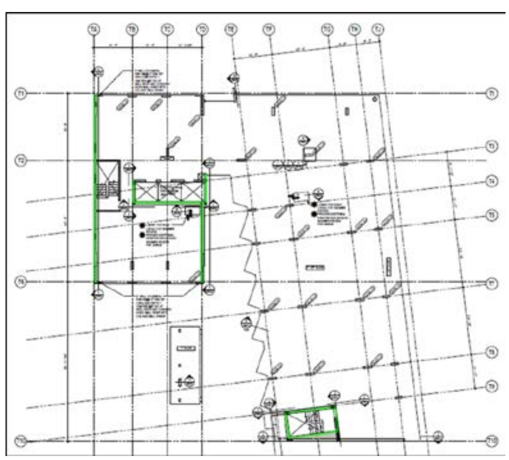

Figure 5. Typical floor plan of the building highlighting (in green) concrete shearwalls as SFRS.

Architectural Non-Structural Components

As described in the previous representative building.

Incremental Cost Summary

Table 7 provides a summary of the incremental costs for the various performance levels ($ values rounded).

Table 7. Incremental Cost Estimate Summary.

Base Cost				**Gross Area**		
$27.9 M				**9,700 m^2**		
Incremental Cost	**Post-Disaster**		**Refugee**		**Operational**	
Structural	0.15%	$40k	0.8%	$214k	1.4%	$400k
Architectural	0.1%	$24,k	0.15%	$43k	0.15%	$43k
Mechanical	TBD	TBD	TBD	TBD	TBD	TBD
Electrical	TBD	TBD	TBD	TBD	TBD	TBD

OVERALL SUMMARY OF BUILDINGS STUDIED

Table 8 summarizes the seven existing BC Housing buildings and their incremental costs, relative to the total original building cost, for the various performance levels.

Table 8. Overall Summary of Buildings Studied.

Incremental Cost	**Code: Post-Disaster**	**Refuge**	**Operational**
Structural	0.2% - 2%	0.2% - 3%	0.6% - 6%
Architectural	0.1%	0.16%	0.16%
Mechanical	TBD	TBD	TBD
Electrical	TBD	TBD	TBD

CONCLUSIONS

This study involved re-designing seven existing buildings, originally designed for normal code requirements, while keeping the existing layouts. Designing new buildings with high seismic performance requirements from the preliminary design stage may allow for an iterative design process resulting in more efficient building layouts that will allow for reductions in the incremental cost increase. Note also that the cost estimates in this study did not include changes in the buildings' usable footprint, such as due to thicker concrete walls, nor the effects of such changes on possible changes to the layout to meet architectural and other code requirements.

As seen in the overall summary for the seven buildings provided in previous section, the incremental cost increase for improved structural performance in an earthquake event is relatively low, even for stringent performance objectives. Similarly, the incremental cost increase for enhanced connections for non-structural components (OFCs) and improved glazing considerations is low.

Therefore, it is recommended that owners/clients seriously consider designing future buildings for higher performance objectives such as "Refugee" and "Operational" level. The structural design adjustments that are most cost effective for a particular building layout and use could be readily evaluated in the Preliminary Design or Design Development phase of a project.

ACKNOWLEDGMENTS

We would like to acknowledge BC Housing for initiating this study and other BC Housing and Ausenco staff that contributed to this project.

REFERENCES

[1] National Building Code of Canada - NBCC 2015, Volume 1. Prepared by the National Research Council of Canada, Ottawa, Canada.
[2] BC Housing Design Guidelines and Construction Standards, March 2018. Prepared by BC Housing, Vancouver, British Columbia, Canada.
[3] ETABS Ver. 16, Computer & Structures, Inc., Structural and Earthquake Engineering Software.