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PERFORMANCE-BASED SEISMIC RETROFIT OF SCHOOL BUILDINGS IN BRITISH COLUMBIA, CANADA – AN OVERVIEW

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Abstract

In 2004, the Province of British Columbia (BC) announced a 10-15 year, $1.5 billion seismic retrofit program for the province's 750 at-risk public schools. The purpose of this program is to quantify the seismic risk of the provinces school buildings and to expedite the seismic upgrading of the most at-risk schools. In order to provide a safe and cost effective implementation of this program, the Association of Professional Engineers of British Columbia (APEGBC), in collaboration with the University of British Columbia (UBC), has developed a performance-based probabilistic methodology along with guidelines for the seismic risk assessment and retrofit of low-rise buildings. The guidelines: *The Seismic Retrofit Guidelines*, (*SRG*), are currently moving towards their 3rd edition (*SRG3*), which will be published in 2016.

This paper summarizes the current state of the province-wide retrofit program and introduces the performance based methodology that has been used to assess and retrofit school blocks. Some of the methodology changes that will be implemented in *SRG3* are also introduced.

Keywords: Seismic retrofit, performance-based design, ground motion selection and scaling, earthquake early warning

1. Introduction

British Columbia (BC), is located on the West Coast of Canada which is a region of moderate to high seismicity. In 2004, the British Columbia Ministry of Education (MOE) initiated a $1.5 billion seismic mitigation program to ensure the safety of all public elementary and secondary schools. This seismic safety program is being implemented by the BC MOE in collaboration with the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC). APEGBC has been contracted to develop a set of state-of-the-art performance-based technical guidelines for structural engineers to use in the seismic risk assessment and retrofit design of school buildings. In undertaking this technical development program, the University of British Columbia (UBC) has been contracted by APEGBC to draft the performance-based technical guidelines based on an extensive applied research program. Each draft of these technical guidelines has been peer reviewed by a BC peer review committee of experienced local consulting engineers and by an external peer review committee comprised of prominent California consulting engineers and researchers.

In total the BC MOE has around 1600 provincial public schools, of which approximately 750 are in regions with a high seismic risk. Currently 339 of these buildings have been classified as "high-risk and are part of the seismic mitigation program (SMP). Of these 339 schools, 50% have started or finished seismic mitigation (see Fig. 1). Of the remaining high-risk blocks, 47% are concrete (shearwalls or non-ductile frames), 24% are wood, 23% are masonry, 3% are steel construction, and 3% are partition walls.

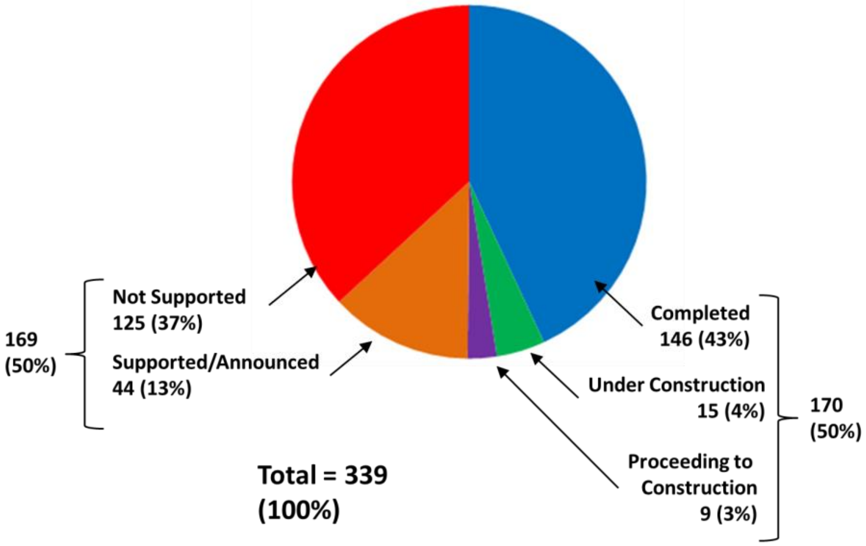


Fig. 1 – SMP Status of BC School Buildings – Mid 2015

The 3rd edition of the *Seismic Retrofit Guidelines* (*SRG3*) will incorporate several modifications based on recent relevant research. First, the seismic hazard will be revised to match the seismic hazard of the 2015 National Building Code of Canada (NBCC), which includes major revisions to the seismic demand along the West Coast of Canada compared to the previous version. Demand will be based on a tri-hazard probabilistic approach in which the contribution of all three BC seismic sources (crustal, subcrustal, and subduction sources) is considered. In order to facilitate improved selection and scaling of ground motion records, conditional spectra (CS) will replace uniform hazard spectra (UHS) as a target for record selection and scaling in several high-hazard locations.

Additionally, many existing prototype models will be improved based on recent testing programs and several new retrofit solutions will be included in order to provide cost-effective retrofit solutions for the new demand levels, which are significantly higher in many locations of BC. The updated guidelines will correspond to the changes made to the NBCC seismic demand and will continue to provide safe, and cost and time efficient retrofit solutions for BC's at-risk school buildings.

2. Performance-based Methodology

The *SRG* methodology is a performance-based methodology which utilizes sophisticated structural models and nonlinear time history analyses to assess the probabilistic performance of structures subjected to seismically induced loads. This methodology uses inelastic deformation, rather than force, to quantify building performance. In the *SRG* methodology, life safety performance is obtained by defining demand requirements that limit the risk of collapse, or excessive deformation, to an acceptable value in a 50 year period.

Most building codes have implemented traditional, force-based methods, in which design forces are estimated based on the elastic spectral response at the period of the structure and the expected degree of ductility. Compared to these methods, a performance-based approach, such as that implemented in *The Guidelines*, can provide much more cost efficient solutions and much more accurate insight into the behavior of the structure during a seismic event [1, 2, 3].

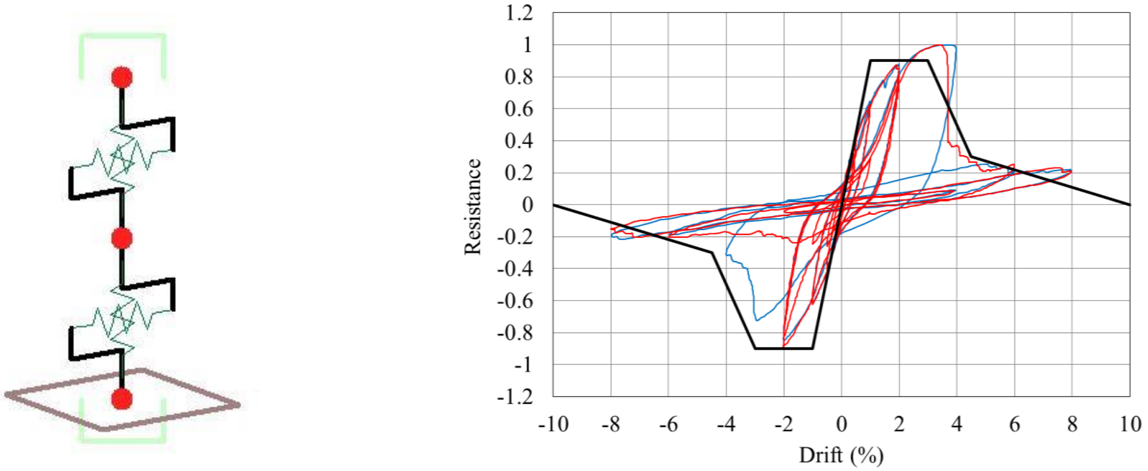
One of the key concepts of the *SRG* methodology is that deformations, rather than forces, are used to estimate the damage and corresponding risk level of a structure. While lateral strength certainly affects the dynamic response of a structure, it is the inelastic deformation levels that govern the damage induced in a structure and are used to set decision limits. This is quite different to force-based methods, typical of design codes, in which pseudo-static lateral forces are applied to the structure in order to design members. In *The Guidelines*, interstory drift levels are utilized to quantify the performance of structures.

In *SRG* the five main principal building elements are 1) vertical load-bearing supports (VLS); 2) lateral deformation resisting systems (LDRSs); 3) partition walls rocking out-of-plane; 4) diaphragms; and 5) connections.

2.1 Nonlinear Models

The *SRG* performance-based methodology requires much more detailed nonlinear models compared to the simple elastic models which can be used in traditional force-based approaches. Performance-based analysis of a structure requires the knowledge of the elastic and inelastic response of the structure, which requires the modeling of the post-yielding behavior of the structure. This allows the entire response of the structure to be captured when subjected to significant ground excitations. To expedite the INDA process, concentrated plasticity elements are used in the modeling of low-rise school buildings. These elements are calibrated to physical test results, where available, or other to other standards such as ASCE/SEI 41-13 [4].

For example, a typical two-story concentrated plasticity model with mass lumped at each story is illustrated in Fig. 2a. The backbone curve of the W-1 prototype, used for modeling blocked OSB/plywood shearwalls, is illustrated in Fig. 2b along with the test results used to develop this backbone curve and corresponding inelastic cyclic behavior.



(a) **(b)**

Fig. 2 – a) Typical *SRG* Concentrated Plasticity Model and b) W-1 Backbone Compared to Cyclic Test Results

2.2 Seismic Hazard

Southwestern BC has a unique seismic setting that includes hazards from three sources: crustal, which occur along shallow faults in the Earth's crust; subcrustal, which occur deep within subducting tectonic plates; and subduction, which are caused by slip between subducting tectonic plates. Geophysical parameters and structural response can vary substantially between these types of earthquakes. Therefore, the definition of seismic hazards for each type of earthquake is an important for the selection of ground motions in this seismic risk assessment project.

The seismicity in Southwestern BC, which is where most of the major population centers in BC are located, is dominated by the subduction of the oceanic Juan de Fuca plate beneath the continental North America plate occurring about 100km west of Southern Vancouver Island – also called the Cascadia Subduction Zone. Large mega-thrust earthquakes have occurred at the interface of these two plates reaching moment magnitudes as high as 9.0 in the past [5]. Subcrustal earthquakes can occur deep below the surface in faults along the Juan de Fuca plate up to 50km deep. Shallow crustal earthquakes, typically less than 20km deep, have been recorded in the North American plate. Currently, the faulting in the North American and Juan de Fuca plates, which causes these two types of earthquakes, is not known, but there is past evidence the proves either of them may occur.

2.3 Ground Motion Selection and Scaling

Conditional spectra (CS) have been employed as target spectra for record selection and scaling in *SRG3*. The three distinct seismic hazard sources in BC: crustal, subcrustal, and subduction, have drastically different characteristics in geophysical properties (depths, magnitudes, etc.) and spectral ordinates and shape. Because of this, it was deemed over-conservative to scale records from each source to the same uniform hazard spectrum (UHS). Lower scaling factors and easier record selection can be introduced by developing individual CS for each source independently, and selecting and scaling records to the proper CS. Additionally, it is extremely unlikely that a ground motion record produces spectral accelerations with a uniform probability of exceedance at all periods (say, 2% probability of exceedance at all periods), which makes scaling to a UHS inherently conservative.

Selecting and scaling records to a CS involves matching the mean spectrum, but also matching the variance about that mean. The variance comes from the standard deviations of the ground motion prediction equations (GMPEs) as well as the epsilon correlation coefficients used to develop the spectrum. Because the variance about the mean spectrum is accounted for in the record selection, the use of a CS is recommended for probabilistic-based methods, such as the *SRG* methodology, where both the mean and standard deviation of the structural response are required [6]. Fig. 3 illustrates 10 example subduction records selected to match the mean and variance of the Victoria, Site Class C subduction CS. Also included is the 2% in 50 year UHS for Victoria, BC. Note that the subduction CMS, conditioned to the UHS at 1 second, falls below the UHS at lower periods. This reflects the nature of the spectral shape of large magnitude subduction earthquakes as observed from previous events.

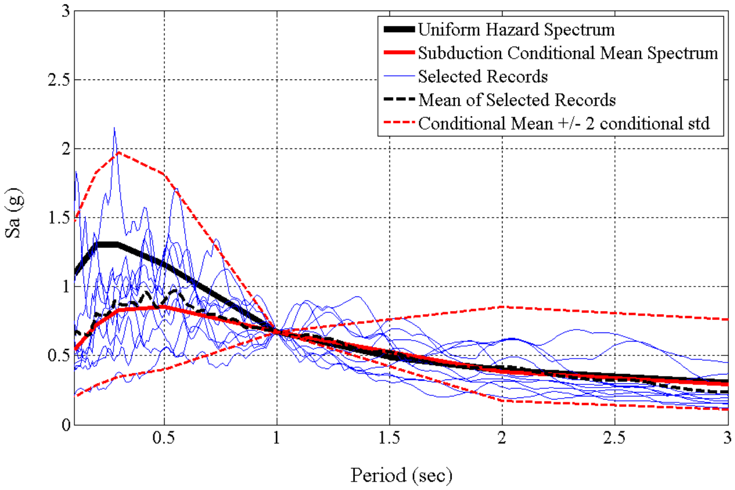


Fig. 3 - Set of 10 Subduction Records Selected and Scaled to Match the Mean and Variance of the Victoria, BC, Site Class C Subduction CS

For more information about CMS and CS the reader is referred to NEHRP, 2011 [6], Lin et al., 2013 [7, 8], Baker and Jayaram, 2008 [9], and Baker and Cornell, 2006 [10]. For more details about the implementation of CS for *SRG3* the reader should see the papers by Bebamzadeh et al., 2015 [11] and Bebamzadeh et al., 2016 [12].

2.4 Incremental Nonlinear Dynamic Analysis

In the *SRG* methodology, the probability of drift exceedance of a structure is determined utilizing INDA [13]. The INDA involves scaling ground motions in 10% increments from 10% to 250% of the code based spectral values (2% in 50 year probability of exceedance) for the considered location.

The INDA comprises 20 different ground motion records for each of the three types of seismic events possible in British Columbia: crustal, subcrustal, and subduction earthquakes (60 records total). The three hazards are analyzed separately and hazard data from the Geological Survey of Canada (GSC) is used to combine the results based on the probability of occurrence of each type of event. This approach permits the probability of excessive damage (drift) to be determined for a specific building life (e.g. 50 years) based on the local seismic hazard data.

The INDA is conducted twice: for records scaled for a 0.5 second conditioned CS, and again for another set of records selected and scaled for a 1.0 second conditioned CS. The governing results between the two cases are used for risk assessment and retrofit demands.

2.5 Tri-hazard Probabilistic Demand Approach

Previous GSC hazard models (used in the 2010 NBCC) combined crustal and subcrustal hazards probabilistically; the subduction hazard was analyzed deterministically and checked separately. Previous versions of *The Guidelines* (e.g. *SRG2*) applied this hazard model and determined risk by considering crustal and subcrustal hazards with a 2% probability of exceedance in 50 years.

In the 5th Generation GSC Seismic Hazard Model, developed for the 2015 NBCC [14], all three sources are analyzed and combined probabilistically to define hazard levels. Correspondingly, for *SRG3*, a probabilistic tri-hazard approach is used to determine risk. This approach will consider the contribution of all three BC seismic sources. The required resistance for life safety will be derived to meet two conditions:

1. Probability of Drift Exceedance (PDE) ≤ 2% in a period of 50 years. This requirement ensures that the maximum inelastic drift does not exceed the appropriate Collapse Drift Limit (CDL) within the acceptable level of risk.

2. Conditional Probability of Drift Exceedance (CPDE) ≤ 25% for near-failure conditions for the 100% code level of shaking (2% in 50 year level) for the governing hazard.

The first condition ensures an adequate level of collapse risk in 50 years considering the complete local seismic setting of the structures, from very low levels of shaking, to excessive levels, far higher than considered in the NBCC. The second condition guarantees that even under a large level of shaking (2% in 50 year level), the structure will still have an appropriate margin against collapse. Because this is a deterministic check (only one particular shaking scenario is being considered), it is not appropriate to use a probabilistic combination of ground motions from separate sources – and thus, only the governing hazard type is considered. This means that the structure is analyzed under each ground motion suite (crustal, subcrustal, and subduction) at a 2% in 50 year shaking level, and only checked for the hazard that governs the results.

The annual rate of drift exceedance for each seismic source is calculated by multiplying the individual CPDE for each level of shaking by its probability of occurrence and then summing (integrating) the contributions from all levels of shaking as follows:

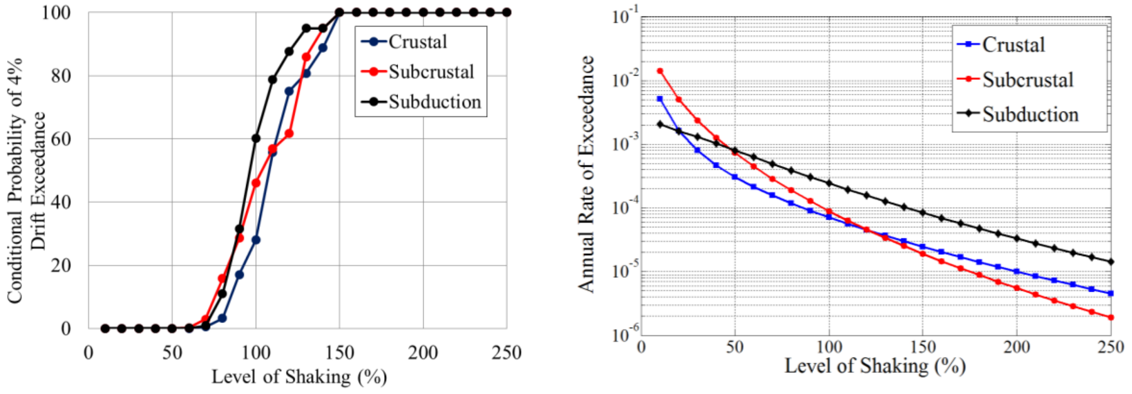
$$\lambda(dr > Dr) = \int CPDE(dr > Dr|_{Sa})\, d\lambda_{Sa} \qquad (1)$$

Where $d\lambda_{Sa}$ is the annual frequency of ground motions with intensity Sa; this is calculated using probabilistic seismic hazard analysis. CPDE is the conditional probability the drift, dr, exceeds a certain drift limit, Dr (typically the CDL), at the given intensity, Sa. The total annual rate of drift exceedance is then calculated by summing up the rates over all three sources of hazards: crustal, subcrustal, and subduction. The total PDE is estimated using the temporal Poisson probability model at given time interval, T (typically 50 years), as shown below:

$$P(dr > Dr) = 1 - \exp(-T \times \Sigma\lambda_i) \qquad (2)$$

Where the summation is over the three earthquake sources: crustal, subcrustal, and subduction.

Fig. 4a illustrates the CPDE for a drift limit of 4% vs. level of shaking curve for the W-1 - blocked OSB/plywood shearwall - prototype with factored resistance equal to 20% of the weight of the structure (%W) and a height of 3m. The 4% drift limit was selected at the CDL for this prototype (see Fig. 2b). Fig. 4b shows the hazard curves (annual rate of exceedance vs. level of shaking) for different seismic sources for Victoria, on Site Class C. In Fig. 4, the 100% level of shaking corresponds to the ground motion with a 2% probability of exceedance in 50 years at period of one second (i.e. 100% of the NBCC code level motion).



(a) **(b)**

Fig. 4 - (a) CPDE vs. Level of Shaking for the W-1 Prototype with a Height of 3m and Factored Resistance of 20%W and (b) Annual Rate of Exceedance vs. Level of Shaking for each Earthquake Source for Victoria, Site Class C (100% level of shaking = 2% in 50 year hazard at period 1.0 sec).

Fig. 5 shows the contribution to the PDE of CDL = 4% from each hazard source in Victoria, for Site Class C, for a wide range of W-1 prototype factored resistances. It can be observed that for all the resistance levels, subduction earthquakes contribute the most to drift exceedance, or damage, for this prototype in Victoria, on Site Class C. A factored (including the NBCC overstrength factor, R_o) resistance of about 20%W is required to ensure that the probability of exceeding the CDL of 4% drift does not exceed 2% in 50 years, which ensures that the life safety requirements are fulfilled.

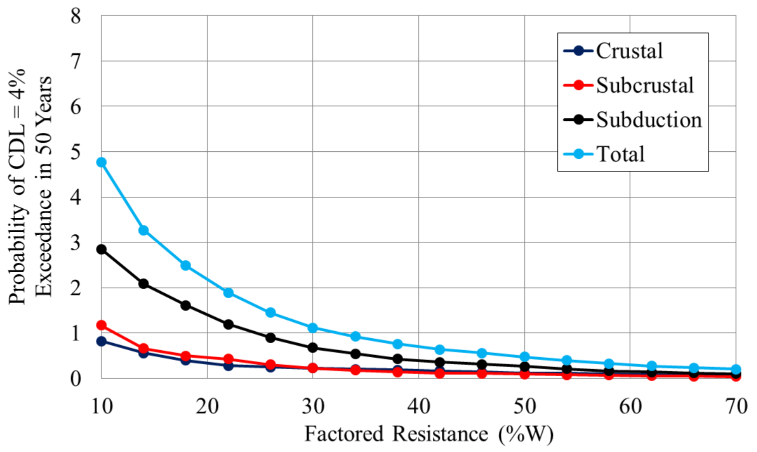


Fig. 5 - PDE of CDL = 4% vs. Factored Resistance for the W-1 Prototype with a Height of 3m for Victoria, Site Class C.

2.6 New Prototypes for *SRG3*

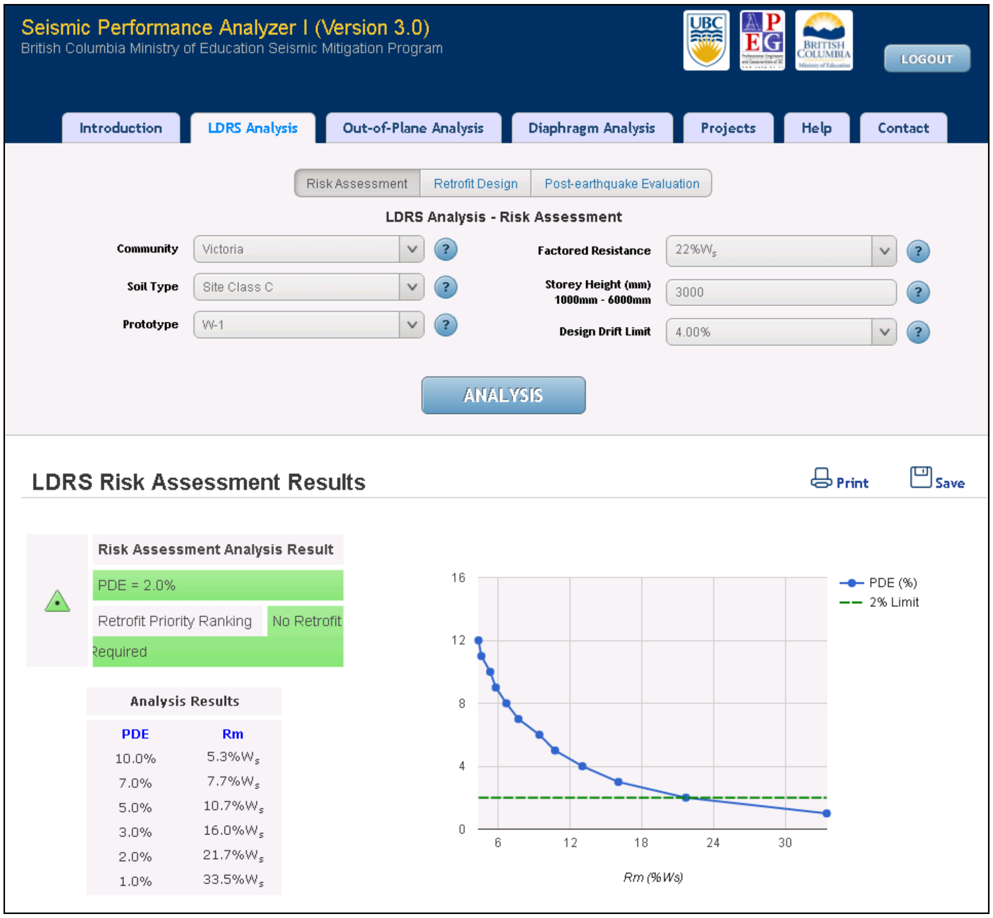
In order to make *The Guidelines* as efficient and cost-effective as possible, it is necessary to count on the capacity of all existing building elements in order to predict the strength of a building (or building block). For example, in woodframe buildings it has been observed that the structures have up to 50% residual capacity from post-earthquake evaluation surveys, experimental results, and numerical analyses. A large percentage of this residual capacity can be attributed to the strength and stiffness of non-structural elements, such as stucco finishing. Due to this, a new stucco prototype (W-5) has been included in *SRG3* to account for the strength and inelastic behavior of this material.

SRG3 will also include a buckling-restrained braced frame (BRBF) prototype (S-10) to be used in the retrofit design of high-risk buildings. BRBFs are easy to install, provide good strength, stiffness, and energy dissipation under seismic loading, and are expected to be very cost efficient retrofit solutions.

2.7 Seismic Performance Analyzer

The Seismic Performance Analyzer, or *Analyzer* for short, is the principal analytical tool used by *The Guidelines*. The tool allows the user to instantly access the complete *SRG* peer-reviewed analytical database. This allows the experienced engineer to combine his practical knowledge and judgment with over 9 million INDA results to demine the risk of his/her particular building block and develop cost-effective retrofit solutions.

The *Analyzer* permits the engineer to quickly analyze the three principal building elements that have analytically complex behavior. These three principal building elements are LDRS', walls rocking out-of-plane and diaphragms. For each of these three building elements, the *Analyzer* performs a risk assessment or a retrofit design. After making the basic parametric selections (input data), the engineer clicks on the Analysis button and the analysis results are instantly displayed.



LDRS Analysis - Risk Assessment

Community: Victoria
Soil Type: Site Class C
Prototype: W-1
Factored Resistance: 22%W_s
Storey Height (mm) 1000mm - 6000mm: 3000
Design Drift Limit: 4.00%

LDRS Risk Assessment Results

Risk Assessment Analysis Result
PDE = 2.0%
Retrofit Priority Ranking: No Retrofit Required

Analysis Results

PDE	Rm
10.0%	5.3%W_s
7.0%	7.7%W_s
5.0%	10.7%W_s
3.0%	16.0%W_s
2.0%	21.7%W_s
1.0%	33.5%W_s

Fig. 6 – Screenshot of the *Seismic Performance Analyzer*

3. Laboratory Testing Programs

A major component of the previous versions of *The Guidelines* along with *SRG3* has been the laboratory testing programs. For *SRG3* an extensive testing program of unreinforced masonry walls (URM) deforming out-of-plane and possible retrofit solutions was conducted [15]. The tests comprised unretrofitted URM walls, and walls retrofit with various systems such as steel U-channels applied with masonry screws; see Fig. 7. All options performed significantly better than the unretrofitted walls and were deemed to be acceptable retrofit solutions.

Another major testing program conducted for *SRG3* was on the effect of long duration ground motions on woodframe structures. Currently, the effect of ground motion duration on the performance of structures is not well understood. Since Southwestern BC, where the majority of the population of the province lives, is in the Cascadia subduction zone, which has the potential to produce large magnitude, long duration earthquakes, it was necessary to assess the effect of this type of motion on structures through physical testing. Accordingly, dynamic shear wall tests were conducted on blocked shearwalls constructed in accordance to Canadian Wood Design Code. The walls were subjected to a recording from the M_w = 9.0 Tohoku, Japan, 2011 megathrust earthquake recorded near Sendai. For more information about this testing program, the reader is referred to the paper by Mulder et al., 2016 [16].

(a) **(b)**

Fig. 7 – Out-of-plane URM specimens: a) bare 4” concrete block wall b) vertical Unistrut® retrofit

4. Early-warning System and Strong Motion Instrumentation

An earthquake early warning system has been developed and implemented by UBC for schools in BC. The system was first developed in collaboration between UBC and The Roman Catholic Archdiocese of Vancouver. The system is based on development of a new, low cost seismic sensor that operates over a network; this provides both local warning at the sensor site and a regional warning across the network. The system is made up of both sensor sites (with two early warning sensor installed) and alarm sites. The alarm sites connect to a central server over the internet, and trigger a warning message either through the local public address system or through sirens. The sensor sites also features the network alarm setup, but can also trigger locally in case of a network disruption. Currently the system includes more than 30 sensor sites and 50 alarm sites. The system was tested in the December 29, 2015 Mw 4.7 Sidney Island Earthquake. The system triggered at St. Patrick’s school on the southern tip of Vancouver Island; schools on the mainland (closer to Vancouver) received as much as 16 seconds of warning due to the use of the network. As part of the BC schools Seismic Mitigation Project $60-100k per site of funding is being provided for instrumentation of the buildings.

Several schools have additionally been instrumented to capture strong motion response. Fig. 8 illustrates an example of the instrumentation layout for strong motion and p-wave detection for a school building made up of six building blocks.

Fig. 8 – Example strong motion sensor in school

5. Post-earthquake Evaluation Guidelines

The Guidelines also include provisions for the post-earthquake evaluation of buildings. These provisions focus on assessing the condition of damaged school buildings to safely withstand aftershocks. The sole performance objective is the life safety of damaged buildings during potential aftershocks.

There are three main cornerstones of the post-earthquake evaluation guidelines:

1. Field assessment – the most important determinant in the safety of a building is what the engineer inspector observes in the field assessment of the damaged building.

2. Evaluation – pre-event evaluation and rating of a school building are vital to provide information for the engineer inspector to assess the extent and ramifications of the damage to that building.

3. Instrumentation – all retrofitted buildings have instrumentation installed to measure both ground motion and storey drift in one or more blocks.

The combination of what the engineer inspector observes (field assessment), expects to see (pre-event evaluation), and what the instrumentation measures provides an efficient and effective basis for assessing the life safety of damaged buildings.

The pre-event evaluation is performed using the same procedures and ground motions that form the basis of the *SRG3 Analyzer* database. The evaluation is done using a deterministic approach for each potential seismic hazard event: crustal, subcrustal, and subduction. For each type of event the damaged block is rated corresponding to the maximum level of shaking that limits the CPDE to 10% at a life safety design drift limit (DDL). The new version of the *Analyzer* will have a page that summarizes this rating for each seismic source, so the engineer inspector can easily and quickly see the expected safety of the structure to aftershocks. This drastically increases the efficiency (time and manpower) and expedites the process of post-earthquake evaluation following a major seismic event.

6. Conclusions

This paper introduced the *SRG* methodology including several of the major changes that will be adopted by the *Seismic Retrofit Guidelines, 3rd Edition* (*SRG3*), for use in the performance-based seismic assessment and retrofit of BC school buildings. These changes are aimed to allow *SRG3* to continue to provide cost-effective retrofit solutions and user-friendly guidelines while evolving to incorporate state-of-the-art knowledge of the seismic hazard in BC.

Three of the main components that will help to reach this goal are the redefinition of target demands from UHS to CS; the adoption of new, more cost-efficient retrofit prototypes along with the revision of several previous prototypes; and the change to a tri-hazard probabilistic approach to classify prototype performance.

The use of CS will facilitate ground motion selection and scaling while being consistent with the hazard demands for each earthquake source. New and revised prototypes will allow engineers to design and benefit from better retrofit solutions. Finally, the change to a tri-hazard probabilistic CPDE check will make the guidelines more probabilistically robust and similar to the new GSC hazard model, which also includes all hazard sources in its probabilistic seismic hazard analysis. The updated guidelines will continue to provide safe and cost and time efficient retrofit solutions for BC's at-risk school buildings.

Additionally, some of the other aspects of the program were introduced including *The Seismic Performance Analyzer*, the laboratory testing programs, the earthquake early warning system and instrumentation, and the post-earthquake evaluation guidelines.

7. Acknowledgements

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