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UPDATES TO THE BRITISH COLUMBIA SEISMIC RETROFIT GUIDELINES, 3RD EDITION

Carlos E. Ventura
Professor, University of British Columbia, Canada
ventura@civil.ubc.ca

Armin Bebamzadeh
Research Associate, University of British Columbia, Canada
armin@civil.ubc.ca

Michael Fairhurst
Graduate Student and Research Assistant, University of British Columbia, Canada
fairhurstmike@gmail.com

Graham Taylor
Principal, TGB Seismic Consultants Ltd., North Saanich, British Columbia, Canada
gwt@tbgsc.bc.ca

W.D. Liam Finn
Professor Emeritus, University of British Columbia, Canada
finn@civil.ubc.ca

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, in collaboration with the University of British Columbia, has developed a performance-based probabilistic method and 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, to be published in 2017.

The 3rd edition of the guidelines (SRG3) will incorporate several modifications based on recent relevant research. First, the seismic hazard will be revised to match the seismic hazard proposed for the 2015 National Building Code of Canada (NBCC), which includes major revisions to the seismic demand along the West Coast of Canada. The change from a uniform hazard spectrum (UHS) to a condition spectrum (CS) will also be adopted in order to facilitate improved selection and scaling of ground motion records. As well, 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. This will replace the previous deterministic approach which only considered crustal and subcrustal hazards with a 2% in 50 year probability of exceedance. Several new building prototype models will be added and many existing prototype models will be improved based on recent testing program results which were not previously available. Unnecessary conservatisms in the prototype models, which existed in previous versions, will be removed so that the analytical models best reflect the observed behaviour of the physical systems. 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.

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. The resulting guidelines: *The Seismic Retrofit Guidelines (SRG)*, are currently moving toward their third edition (SRG3), to be published in 2017. 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.

The main objectives of the guidelines are enhanced life safety, cost effective retrofits, and user-friendly technical guidelines. Life safety is achieved through minimizing the probability of excessive structure damage by use of rational and peer-reviewed performance-based methods of earthquake damage estimation. Cost effective retrofit strategies are achieved through the use of innovative retrofit techniques and the development of rational minimum resistance requirements in order to achieve life safety performance. Probabilistic incremental nonlinear dynamic analysis (INDA) (Vamvatsikos and Cornell, 2002) using ground motions that represent the seismic setting in BC is used to develop these minimum requirements. Interstorey drift is used as surrogate for structural damage to assess the risk of the buildings. User-friendly technical guidelines have been developed and presented in the form of pre-determined minimum lateral resistance requirements and a simple-to-use seismic performance calculator to enable an engineer to perform a seismic risk assessment or a retrofit design for any of the structural systems, typical of schools in the region.

For SRG3, the 2015 Geological Survey of Canada (GSC) hazard model for Western Canada, which is being proposed for adoption by the 2015 National Building Code of Canada (NBCC), is being used to define the hazard for BC school buildings (Halchuk et al., 2014). The changes to the 2015 hazard model include a significant reinterpretation of the Cascadia subduction zone hazard, which has a drastic effect on the seismic hazard in BC, including significant increases on BC’s South-western coast. In order to adapt to this new hazard level, several components of the SRG methodology were investigated, including the target spectrum for record scaling and selection, the prototype models, and the effect of subduction sources on the performance of the structures.

2. 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. SRG2 applied this hazard model and determined risk by considering crustal and subcrustal hazards with a 2% probability of exceedance in 50 years. The required resistance for life safety was derived to meet two conditions:

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

(b) Conditional Probability of Drift Exceedance (CPDE) ≤ 25% for near-failure conditions for the 100% code level of shaking.

In the 5th Generation GSC Hazard Model, proposed for the 2015 NBCC, all three sources are analyzed and combined probabilistically to define hazard levels. Correspondingly, for SRG3, it is proposed to use a probabilistic tri-hazard approach to determine risk. This approach will consider the contribution of all three BC seismic sources: crustal, subcrustal, and subduction. The annual rate of drift exceedance is calculated by multiplying the individual CPDE for each level of shaking by its probability of occurrence (based on data from the Geological Survey of Canada) and then summing the contributions from all levels of shaking and each hazard type as follows:

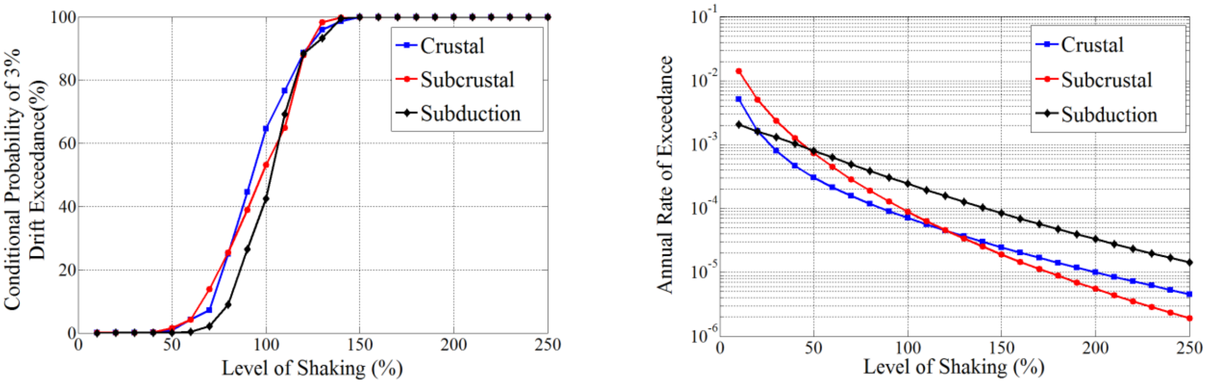
$$\lambda(dr > Dr) = \int CPDE\left(dr > Dr|_{Sa}\right).d\lambda_{Sa} \tag{1}$$

where $d\lambda_{Sa}$ is the annual frequency of ground motions with intensity S_a, which is directly calculated from the Probabilistic Seismic Hazard Analyses. CPDE is the conditional probability the drift, *dr*, exceeds a certain drift limit, *Dr* , at the given intensity, S_a. 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 PDE is estimated using the temporal Poisson probability model at given time interval *T* as shown in Equation 2:

$$PDE(dr > Dr) = 1 - \exp\left(-T\sum_{i=1}^{n}\lambda_i\right) \tag{2}$$

Where *n* is the number of earthquake sources.

Fig. 1a illustrates the CPDE for DDL = 3% vs. level of shaking curve for the W-1 - blocked OSB/plywood shearwall - prototype with factored resistance of 26% of the weight of the structure (%*W*) and a height of 3m. Fig. 1b shows the hazard curves (annual rate of exceedance vs. level of shaking) for different seismic sources for Victoria, on Site Class C. In Fig. 1, the 100% level of shaking corresponds to the ground motion with a 2% probability of exceedance in 50 years at period of one second.



(a) **(b)**

Fig. 1 – (a) CPDE vs. Level of Shaking for the W-1 Prototype with a Height of 3m and Factored Resistance of 26%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).

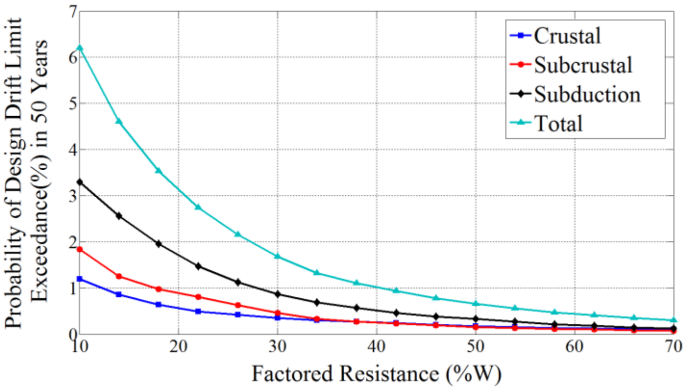


Fig. 2 – PDE of DDL = 3% vs. Factored Resistance for the W-1 Prototype with a Height of 3m.

Fig. 2 shows the contribution to the PDE of DDL = 3% from each hazard source in Victoria, for Site Class C, for a wide range of W-1 prototype factored resistances. We can observe 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 resistance of 26%W is required to ensure that the probability of exceeding the DDL of 3% drift does not exceed 2% in 50 years which ensures that the life safety requirements are fulfilled.

3. Target Spectrum: Conditional Spectrum

It is being proposed to use conditional spectra (CS) as target spectra for record selection and scaling in SRG3. BC has three distinct seismic hazard sources: crustal, subcrustal, and subduction, each of which has 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.

Fig. 3 illustrates the 2015 Victoria, Site Class C, UHS compared to a conditional mean spectrum (CMS), conditioned at a period of 1.0 seconds, for each BC seismic source. From this figure, it can be seen that crustal and subduction records which have a 1.0 second spectral acceleration with a low probability of exceedance (2% in 50 years) tend to have similarly high spectral accelerations at lower periods, while spectral accelerations at higher periods tend to decrease compared to the UHS. This is typical of lower magnitude ($M_w < 8.0$), short distance, crustal and subcrustal records, which tend to have high energy in short periods and less energy at longer periods. On the other hand, subduction records, which typically come from large magnitude events ($M_w > 8.0$) at far distances, have more energy in their longer periods. This can be clearly seen in the subduction CMS, which has lower spectral accelerations compared to the UHS at short periods and similar accelerations at longer periods. This means a subduction event that produces a 2% in 50 year spectral acceleration at 1.0 second will likely produce spectral accelerations with a similar probability of exceedance at longer periods.

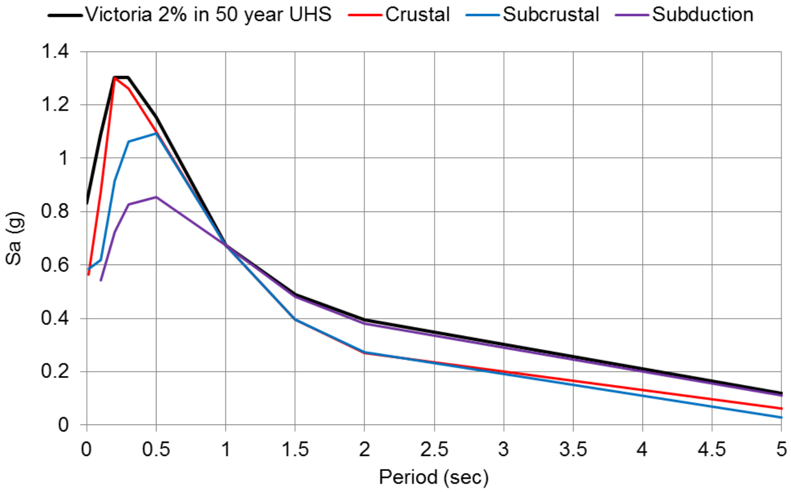


Fig. 3 – Victoria 2% in 50 Year UHS and CMS for Crustal, Subcrustal, and Subduction Sources Conditioned at 1.0 second

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 deviations of the ground motion prediction equations as well as the uncertainty in 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 (NEHRP, 2011).

For more information about CMS and CS the reader is referred to NEHRP (2011), Lin et al. (2013a and b), Baker and Jayram (2008), and Baker and Cornell (2006). For more details about the implementation of CS for SRG3 the reader should see the companion paper: “Selection of Ground Motions for the Seismic Risk Assessment of British Columbia School Buildings for the Proposed 2015 NBCC Ground Motions” (Bebamzadeh et al., 2015).

4. High-Performance Prototypes

In the SRG methodology, engineers would define the components in their structure as one of the available prototypes. A wide range of prototypes was considered ranging from steel frames, to concrete frames and walls, to timber walls, to out-of-plane masonry walls, to rocking elements, to different types of diaphragms. These prototypes were modelled based on physical test results and expert judgement and comprised all of the commonly used structural systems in BC low-rise school buildings. However, since these prototypes were developed for use in the assessment of existing building components, many of them were intentionally made conservative, and may have not been appropriate to use for the assessment of modern construction retrofit components.

Two commonly used prototypes for the retrofit of schools by BC engineers are woodframe shearwalls and flexural reinforced concrete shearwalls. Recent testing programs and guidelines were examined and compared to the previous SRG models for these systems in order to develop “high-performance” versions of these prototypes. These prototypes are less conservative than previous models, which will result in more cost-effective possible retrofit solutions. These models are also calibrated to a wide variety of test results and are more sophisticated and accurate compared to previous prototype models.

4.1. Woodframe Shearwall Modelling

The SRG2 blocked OSB/plywood shearwall model (W-1) was developed based on monotonic and cyclic tests performed at UBC, and is illustrated, along with the cyclic test results, in Fig. 4.

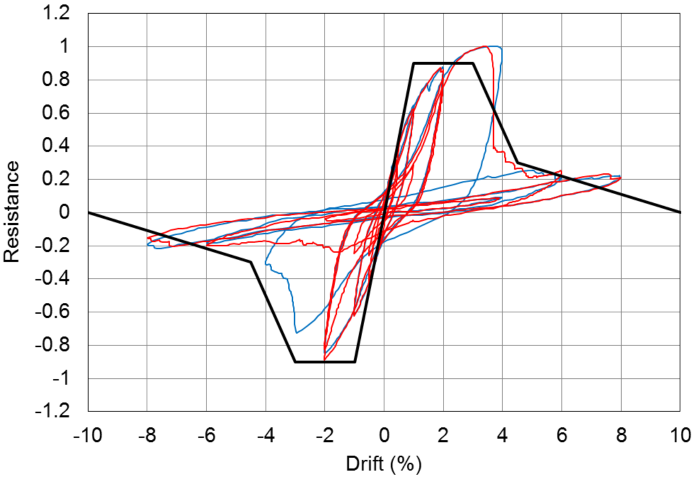


Fig. 4 - SRG2 W-1 Backbone Model with Cyclic Test Results

As a comparison, the default FEMA P-807 (FEMA, 2012) backbone curve models are presented in Fig. 5. FEMA P-807 offers default backbone curves for a variety of typical nail sizes and spacing. The curves are drawn as the mean values from a wide range of cyclic test results from testing programs including City of Los Angeles (2001), Pardoen et al. (2003), and Gatto and Uang (2002); the two latter being part of the CUREE Woodframe Project. As observed in Fig. 5, yielding typically occurs around 1% drift, while strength loss begins at around 3-4% drift. All of the curves are dropped to zero resistance at 5% drift, which may not be accurate, since most of the considered tests were only conducted to 4% drift. This seems to be a conservative estimate made by the authors due to the lack of data at higher drift values.

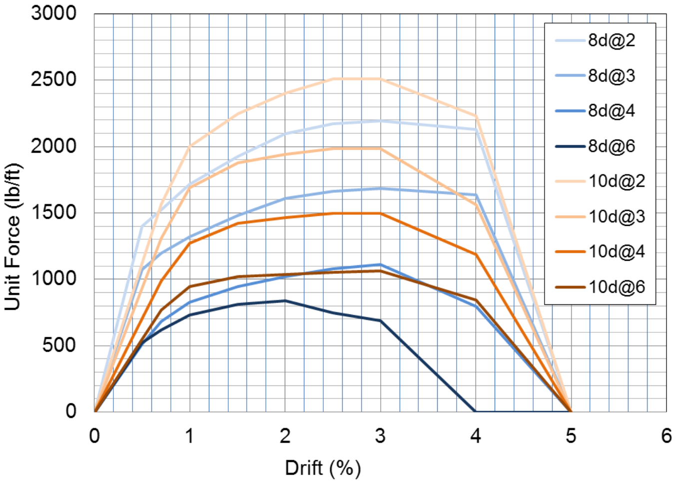
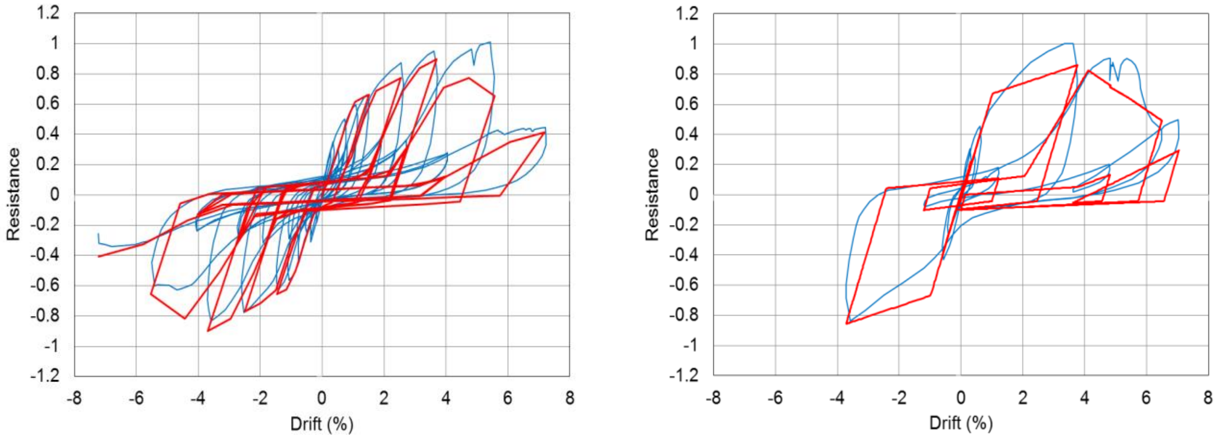


Fig 5. – Default FEMA-P807 Backbone Curve Models

Comparing the SRG2 backbone curve in Fig. 4 with the FEMA-P807 backbone curves in Fig. 5 shows several discrepancies. First, the onset of strength degradation in the SRG2 W-1 model occurs at lower drifts compared to many of the FEMA P807 models, especially those with smaller nail spacing. Second, the SRG2 W-1 backbone curve was capped at 90% of the maximum observed resistance from the testing protocol. This cap was to account for the strength loss that occurred when the loading direction was reversed once the wall had already damaged in the previous load cycle.

This gives two clear options that were used to the develop high-performance woodframe shearwall prototype: 1) To use a higher drift limit for the onset of strength degradation (providing certain nailing requirements can be met, i.e. 2" or 3" nail spacing – which is possible for a retrofit wall). 2) To model strength deterioration and use the full capacity of the wall rather than the 90% limit.



(a) **(b)**

Fig. 6 - UCSD Test Modeled with Deterioration Compared to Test Results: (a) CUREE Loading and (b) Near Fault (NF) Loading (Gatto and Uang, 2002)

The high-performance prototype, denoted SRG3 W-5, was calibrated to a variety of reverse-cyclic physical tests comprising many distinct loading protocols. Fig. 6 illustrates two examples of the calibrated results of two similar walls loaded with very different loading protocols (Gatto and Uang, 2002). Fig. 7 shows the new backbone curve, which was based on the FEMA P807 8d nail at 2” and 3” models, compared to the SRG2 W-1 backbone curve. The Pinching4 model implemented in OpenSees was used for this model with cyclic strength and stiffness deterioration (Lowes et al., 2003).

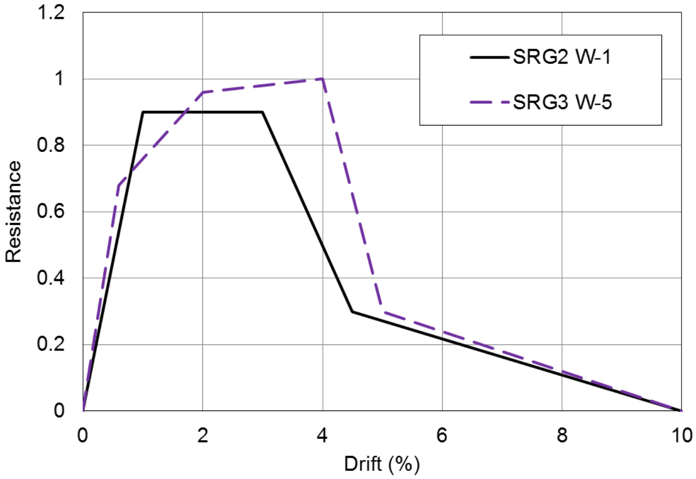


Fig. 7 – SRG3 W-5 Prototype Backbone Curve vs. SRG2 W-1 Prototype Backbone

Table 1 summarizes the required resistance, as a percentage of the total weight of the structure (R_m) for the SRG2 W-1 model with 2010 and 2015 ground motion levels and for the new W-5 prototype with the 2015 motions. Analyses were run using both UHS scaled motions and CS selected and scaled motions.

Table 1: R_m (%W) Summary for Vancouver and Victoria, UHS and CS, Site Class C, Height = 3000mm for Blocked OSB/Plywood Shearwalls

	Victoria		Vancouver	
	UHS	**CS**	**UHS**	**CS**
SRG2 W-1 2010 Motions	8.6	–	7.0	–
SRG2 W-1 2015 Motions	27.7	26.8	13.6	13.2
SRG3 W-5 (FEMA 8d@2,3”)	25.2	24.0	11.4	11.4

4.2. Flexural Concrete Shearwall Modelling

A similar approach was implemented for the SRG moderately ductile reinforced concrete shearwall controlled by flexure (C-6). First, testing program results were considered to validate the modelling parameters. The database developed by Birley (2012), was particularly useful and contained results from over 50 reinforced concrete reverse-cyclic tests from 18 testing programs. The modelling parameters recommended by ASCE/SEI 41-13 (ASCE, 2013) were also considered. Fig. 8 illustrates the SRG C-6 prototype backbone compared to similar backbones from ASCE/SEI 41-13 for walls with both high and low shear demand/capacity ratios.

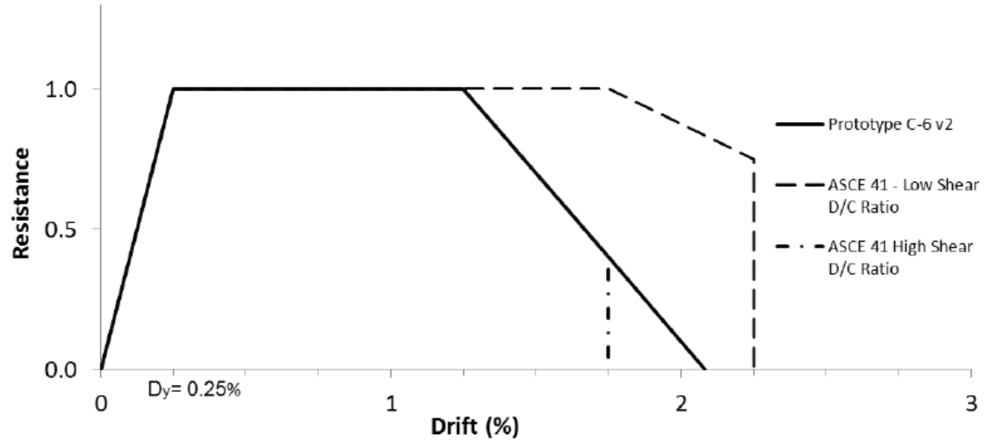
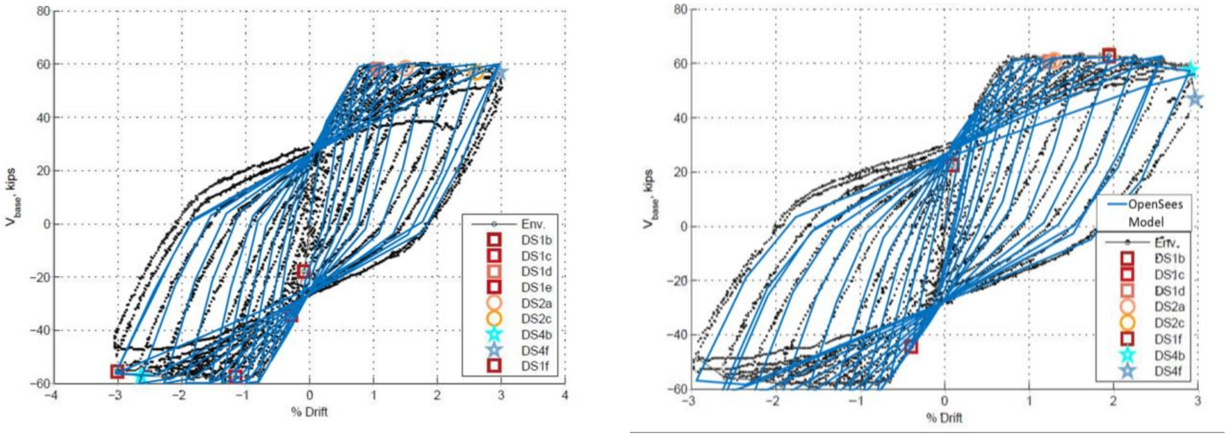


Fig. 8 – Comparison of SRG C-6 Backbone Curve Compared to ASCE/SEI 41-14 Recommendations

From Fig. 8 it can be seen that the SRG implementation is similar to that for shearwalls with a high shear demand/capacity ratio. Observation of the database compiled by Birley (2012) also showed many walls with higher drift limits before the onset of strength loss. However, these walls were also noted to have a clear pinched hysteretic response as well as some in-cycle strength and stiffness deterioration.

Based on this observed behavior, several concrete prototype backbones were developed and calibrated to specific test results. For the new flexural concrete shearwall prototype a model, called C-7, was developed, based on tests with low axial and shear demands and a high amount of end zone confinement. Fig. 9 shows two examples of this calibrated model compared to test results from Liu (2009). The model was developed using the Pinching4 material implemented in OpenSees (Lowes et al., 2003)



(a)

(b)

Fig. 9 – Calibrated OpenSees Concrete Shearwall Model (C-7) Compared to Test Results: (a) LiuW1 (b) LiuW2 (Birley, 2012; Liu, 2009)

The ASCE 41-13 backbone curve for flexural concrete walls with confined boundaries and low axial and shear demand/capacity ratios was used for this prototype. Use of this prototype will require engineers to make sure these conditions are met, which is possible in many retrofit applications. Table 2 summarizes the R_m results for the new and current SRG flexural concrete shearwall prototypes.

Table 2: Rm (%W) Summary for Vancouver and Victoria, UHS and CS, Site Class C, Height = 4500mm for Moderately Ductile Reinforced Concrete Shearwalls Controlled by Flexure

	Victoria		Vancouver	
	UHS	**CS**	**UHS**	**CS**
SRG2 C-6 2010 Motions	15.5	-	13.2	-
SRG2 C-6 2015 Motions	29.5	27.1	14.8	13.3
SRG3 C-8 2015 Motions	24.0	22.0	12.0	9.9

5. Conclusion

This paper described several of the major changes that will be adopted by the *Seismic Retrofit Guildeines, 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 more cost-efficient, better performing retrofit prototypes; and the change to a tri-hazard probabilistic approach to replace the previous deterministic approach in classifying 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 prototypes will allow engineers to design and benefit from better retrofit solutions. These prototypes are intended to relieve components that can meet certain, stricter, detailing requirements from the high resistance demands required for prototypes intended for the assessment of existing structures.

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, even with the new demands imposed by the 2015 GSC hazard model.

6. Acknowledgements

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7. References

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