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# OVERVIEW OF THE BRIDGING GUIDELINES FOR THE SEISMIC RETROFIT OF BC SCHOOLS

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## ABSTRACT

In 2004, the Province of British Columbia, on the West Coast of Canada, announced a 10-15 year, $1.5 billion seismic retrofit program for the province's 750 at-risk public schools. The purpose of this earthquake preparedness initiative is to accelerate the upgrading of school public safety in the moderate and high seismicity regions of the province. Given the magnitude of the mitigation program, the province's Ministry of Education and the federal agency Western Economic Diversification Canada made a commitment to support the development of state-of-the-art performance-based seismic engineering technology for achieving optimum safety within a cost-effective mitigation framework, which could not be achieved based on current practice. This paper gives an overview of the formulation of performance-based structural assessment and retrofit design guidelines, which are currently being used by engineers to determine retrofit strategies for schools in British Columbia.

## Introduction

The primary focus of the Ministry of Education's (MEd) seismic mitigation program in British Columbia (BC) is the structural upgrading of at-risk public school buildings located in areas of moderate or high seismicity in BC.

One crucial component to the retrofit design process is a multi-year development of policy and technical standards that are to guide the mitigation program. The development of these standards commenced in 2004. The objective of these standards is the development of rational, performance-based cost-effective retrofit strategies that reflect community-based life safety standards.

Given the need to commence retrofit construction prior to the completion of the multi-year standards development, an interim set of Bridging Guidelines was developed in 2005 and 2006. This paper provides an overview of the development of the Second Edition Bridging Guidelines (APEGBC 2006) for the seismic upgrading of low-rise school buildings in British Columbia, as well as improvements planned for the final Technical Guidelines.

Performance-based seismic design engineering for low-rise buildings is uncommon in British Columbia

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and the rest of Canada, despite low-rise buildings accounted for the majority of the at-risk building stock. The recently released 2005 edition of the National Building Code of Canada (NBCC 2005) states overall performance objectives but is not intended for the upgrade of existing buildings, and typically results in overly-conservative and costly seismic retrofits.

The Bridging Guidelines provide performance-based seismic design engineering solutions in a simple and rational format. The technical requirements of the guidelines are based on non-linear time history analysis that estimates inelastic earthquake damage as a function of seismicity, soil type, lateral structural system and a system-dependent governing drift limit.

## Background and Development of Guidelines

The development of these seismic retrofit guidelines was undertaken by collaboration between government (Ministry of Education), industry (APEG-BC and local consulting firms) and academia (University of British Columbia).

The first project was the Performance-based Seismic Risk Assessment Tool UBC-100, completed in 2004. UBC-100 was successfully used to priority rank 125 high risk schools, which aided the Ministry of Education in deciding where the initial funds would be spent.

The 1st Edition of the Bridging Guidelines (EERF 2005) was completed in 2005, and was used by local practitioners until October, 2006, when the 2nd Edition Bridging Guidelines (APEGBC 2006) were released.

### Peer Review Process (PRC)

APEG-BC assembled a “Seismic Risk Task Force” committee to pier review the development of UBC-100. This same group, comprised of leading, local, highly experienced engineers, continued to serve in a peer review capacity for the Bridging Guidelines, and the eventual Technical Guidelines.

The peer reviewers not only provided critique at regular meetings, but also tested the Bridging Guidelines on school feasibility and retrofit design projects.

### External Peer Review Process (EPR)

Prominent engineers from California were involved in reviewing the analysis procedures and other technical details. Their insight on non-linear dynamic analysis and developing guidelines provided valuable feedback which greatly improved the Bridging Guidelines.

### Local Practitioners

The Bridging Guidelines were developed to be used by local engineers. Seminars on the 1st and 2nd Edition Guidelines were given to disseminate the use of the guidelines to local engineers. In addition, a series of workshops and office visits have provided a less formal setting for practitioners to ask questions and give feedback on the Bridging Guidelines. Both editions of the guidelines developed a Q&A document (after the workshops and office visits) which was circulated to all companies which attended the seminars.

### Scope of Guidelines

The three overall objectives of the Bridging Guidelines are: 1) enhanced life safety structural performance, 2) cost-effective retrofits; and 3) user-friendly technical guidelines. The enhanced life safety philosophy of these guidelines is accomplished through minimizing the probability of structural collapse. Cost-effective strategies are achieved by providing a displacement-based rational method to account for the resistance of all new and existing structural materials. User-friendly technical guidelines have been developed and presented in the form of pre-determined minimum lateral resistance requirements. This format permits the practitioner to capitalize on the benefits of advanced performance-based engineering techniques without subjecting them to undertake complex analyses.

## Performance Objectives

The principal performance objective of the Bridging Guidelines is life safety. Damage mitigation and immediate occupancy are performance objectives not specifically addressed in the current guidelines. In the guidelines, the risk to life safety is managed by limiting the allowable drift of a given lateral deformation resisting system (LDRS) to be less than or equal to a corresponding instability drift limit (ISDL). The ISDL represents the maximum allowable drift of a given LDRS to maintain a low probability of structural collapse, which would lead to a catastrophic number of casualties. The risk to life safety from the failure of heavy partition walls is also included in the guidelines.

The performance objectives adopted in the Bridging Guidelines are similar to those given in the FEMA 356 (ASCE 2000) and FEMA 424 (FEMA 2004) publications. The ISDL values are a significant component of these performance objectives, and guidance on their values was taken from a combination of FEMA 356 and various experimental programs.

One significant difference is that the Bridging Guidelines uses the results of the mean plus one standard deviation from a suite of ground motions for the retrofit design level. This results in an overall demand greater than the design ground motion (2% in 50 years). The assessment of schools is based on 80% of the retrofit requirements.

## Seismic Zones and Soil Type

In the Bridging Guidelines, the province of British Columbia has been divided into six seismic zones based on the spectral response acceleration values for a period of 1 second, as prescribed in the 2005 National Building Code of Canada (NBCC 2005). Figure 1 shows the seismic zones for the south-west corner of British Columbia.

Soil hazard maps were developed for the two most populous regions of the province; the Lower Mainland in the southwest corner of BC and Greater Victoria on Vancouver Island. These two soil hazard maps demarcate the geographic boundaries of the five major soil types, Site Class A (hard rock) to Site Class E (soft soil), which are based on the NEHRP soil classes for susceptibility to ground motion amplification. Figure 2 shows the soil hazard map for the Greater Regional District of Vancouver.

## Prototypes

The range of common low-rise school buildings are modeled by a number of building prototypes that are differentiated by construction material and the main Lateral Deformation Resisting System (LDRS). The LDRS is comprised of vertical building elements that have similar seismic performance characteristics and that generate resistance to inter-storey horizontal shear deformations in the building. A total of 17 LDRSs are currently included considered in the Bridging Guidelines as listed in Table 1. Note that the ductility descriptions are the same as those used in the Table 4.1.8.9 of the 2005 NBCC.

Additionally the 2nd Edition Bridging Guidelines has 6 diaphragm prototypes, which are used for inelastic diaphragm retrofit designs and assessments. These are given on Table 2.

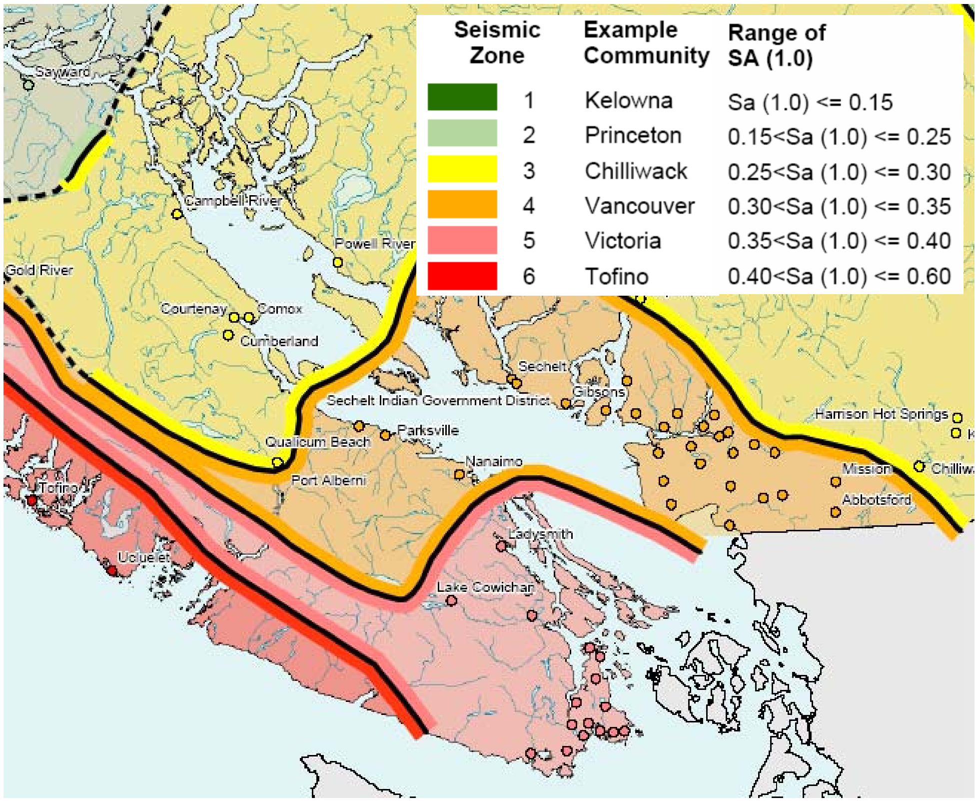


Figure 1. Seismic Hazard Map for South Western British Columbia.

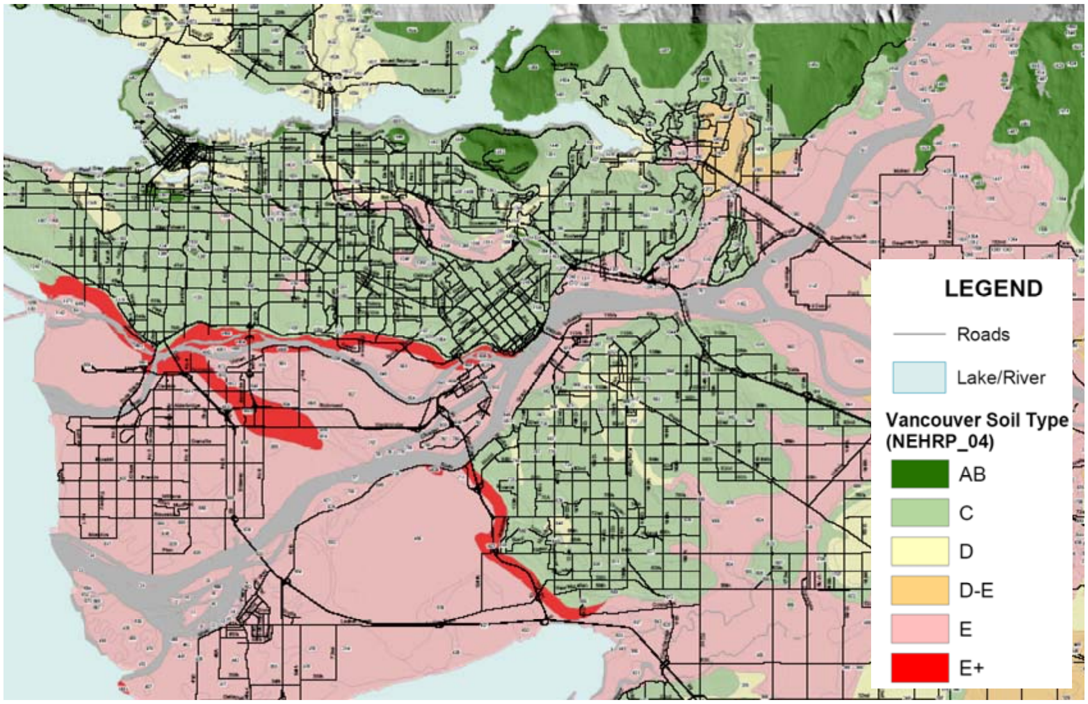


Figure 2. Soil Type Map for the Greater Vancouver Regional District.

Table 1. Listing of Lateral Deformation Resisting Systems.

| Material Group | Prototype No. | Prototype Description and Failure Mode | ISDL | $R_o$ |
|---|---|---|---|---|
| Wood | W-1 | Blocked OSB/plywood shearwall | 4.0% | 1.7 |
| | W-2 | Unblocked OSB/plywood shearwall | 4.0% | 1.7 |
| Steel | S-1 | Concentric braced frame (tension only) | 4.0% | 1.3 |
| | S-2 | Concentric braced frame (tension/compression) | 1.0-2.5% | 1.3 |
| | S-3 | Eccentric braced frame | 4.0% | 1.5 |
| | S-4 | Moment frame (moderately ductile) | 4.0% | 1.5 |
| Concrete Masonry | M-1 | In-plane unreinforced shearwall bed-joint sliding | 1.5% | 1.5 |
| | M-2 | In-plane reinforced masonry | 1.5% | 1.5 |
| Reinforced Concrete | C-1 | Shearwall (moderately ductile) | 2.0% | 1.4 |
| | C-2 | Shearwall (conventional construction) | 1.5% | 1.3 |
| | C-3 | Moment frame (ductile) | 4.0% | 1.7 |
| | C-4 | Moment frame (moderately ductile) | 4.0% | 1.4 |
| | C-5 | Moment frame (conventional construction) | 4.0% | 1.3 |
| Clay Brick Masonry | B-1 | In-plane shearwall bed-joint sliding | 1.0% | 1.5 |
| Rocking | R-1 | Low Aspect Ratio Rocking Element | 4.0% | 1.0 |
| | R-2 | Medium Aspect Ratio Rocking Element | 4.0% | 1.0 |
| | R-3 | Higher Aspect Ratio Rocking Element | 4.0% | 1.0 |

Table 2. Listing of Diaphragm Prototypes.

| Material Group | Prototype No. | Diaphragm Description | $R_o$ |
|---|---|---|---|
| Wood | D-1 | Blocked OSB/plywood | 1.70 |
| | D-2 | Unblocked OSB/plywood | 1.70 |
| Steel | D-3 | Steel Deck - Type A | 1.67 |
| | D-4 | Steel Deck - Type B | 1.67 |
| | D-5 | Steel Braced Frame (Tension Only) | 1.30 |
| | D-6 | Steel Braced Frame (Tension/Compression) | 1.30 |

## Analysis Program for Resistance Tables

Non-linear analyses were used to determine the inelastic deformation performance of the LDRSs and diaphrgams in the Bridging Guidelines. The following three independent non-linear analysis tools were used to compile the analysis results database:

(1) CANNY, a commercial 3-D dynamic analysis software package (Li, 2004)
(2) Quakesoft, in-house customized software that models each lateral resisting system in each storey by a non-linear lateral deformation resisting element and,
(3) FEMA 440 (ATC 2005), the refined displacement modification method for use with non-linear static (push-over) analysis.

Quakesoft was used to generate the response of all 17 prototype buildings in the 5 seismic zones on 3 site classes (C, D and E). CANNY and FEMA-440 were used to perform a validation of the results from the Quakesoft. Quakesoft was also used to generate the diaphragm resistance tables, while CANNY was used for validation.

Both Quakesoft and CANNY used a suite of 10 ground motions. The ground motions were all crustal in nature and came from the 1994 Northridge, 1989 Loma Prieta, and 1971 Imperial Valley earthquakes.

The records were scaled to the corresponding design spectra of the 2005 NBCC for each combination of seismic zone and site class. Mean plus one standard deviation values of the suites were then used in the resistance tables. Details of the ground motions can be found in Commentary C of the 2nd Edition Bridging Guidelines (APEGBC 2006)

Since the FEMA-440 Displacement Modification Method does not require time histories, merely an acceleration spectrum. As such, the 2005 NBCC spectra were used directly.

All prototypes, or LDRSs, were modeled as a 2-D two-storey building, with lateral shear spring models at each level. Masses were lumped at the first floor and roof. The prototypes differ in the backbone curve (monotonic load-displacement relationship) and hysteretic model (cyclic loading rules). Figures for the backbone curves and the hysteretic models can be found in the Bridging Guidelines Commentary C (APEGBC 2006).

Diaphragm models are more complex than those of the LDRSs. Each consists of two end walls (modeled as one of the LDRSs) and a series of diaphragm shear elements, with masses lumped at each diaphragm node.

The outcome of the extensive analysis was a set of resistance tables that list the minimum required strength values, for retrofit, to maintain a given drift limit. Each resistance table was for a specific prototype and seismic zone. A strength value is given to limit the drift to 1.0%, 1.5%, 2.0%, 3.0% and 4.0% on a given site class. The table also provides a plot of the required resistance vs. maximum drift. All values on the resistance tables have been divided by the code based Ro (given on Tables 1 and 2), such that they are compatible with the material design codes. An example resistance table for blocked plywood shearwalls is given in Figure 3.

The diaphragm tables are different. Drift limits are replaced with span lengths. The diaphragm resistance criteria is based on a maximum shear strain based on material, and an overall maximum displacement of 200mm. A diaphragm resistance table is given in Figure 4.

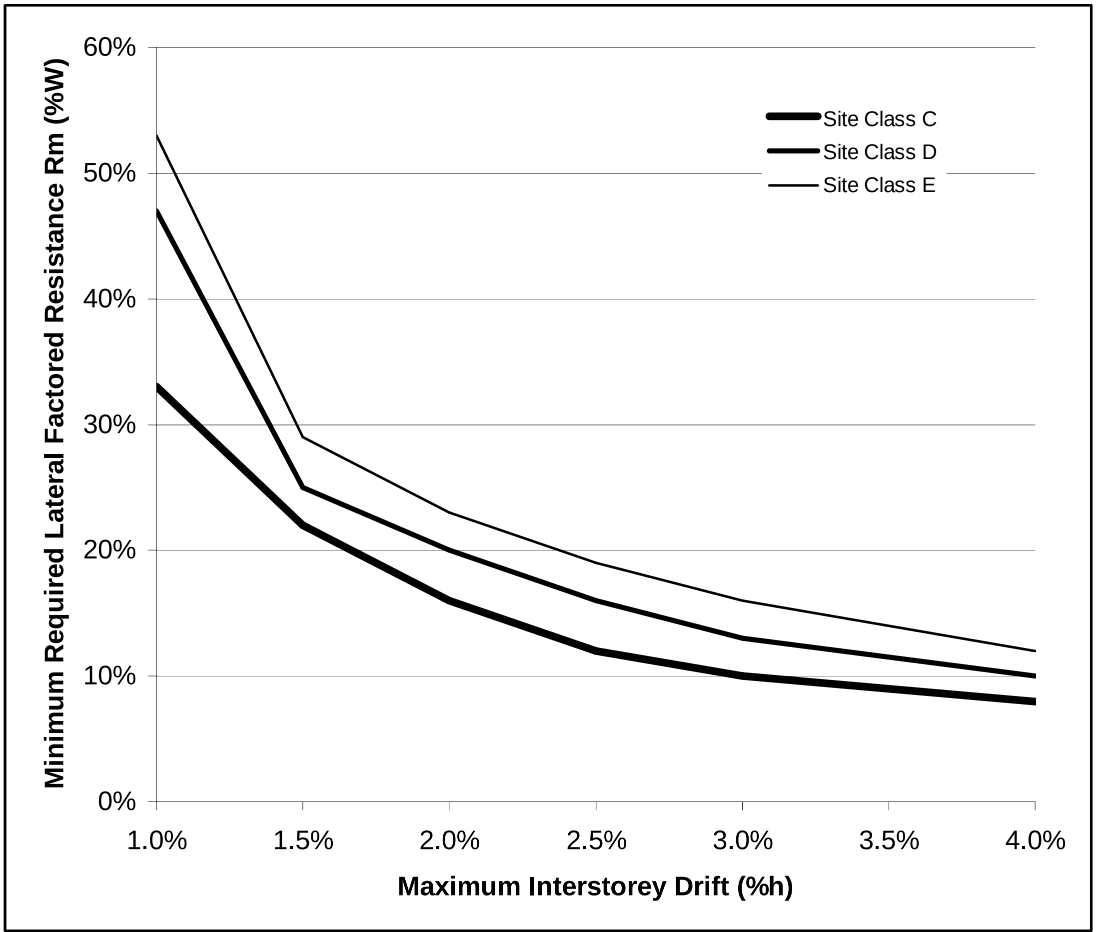
## Validation of Resistance Tables

Each LDRS and diaphragm prototype was validated with an independent set of analyses. This validation was done to first check if there was an error in the modeling and secondly to compare the results to the 2005 NBCC. For most prototypes, this was equal to 60% of the seismic static force levels.

The validation process did find inconsistencies in the analysis results. This led to changes and re-analysis. A sample of one of the final validation charts is shown in Figure 5.

A third, more limited, set of analysis was done by the EPR. This analysis used the computer program RAM-Perform and in general produced less conservative values than the Quakesoft analysis.

**W-1 Zone 4**

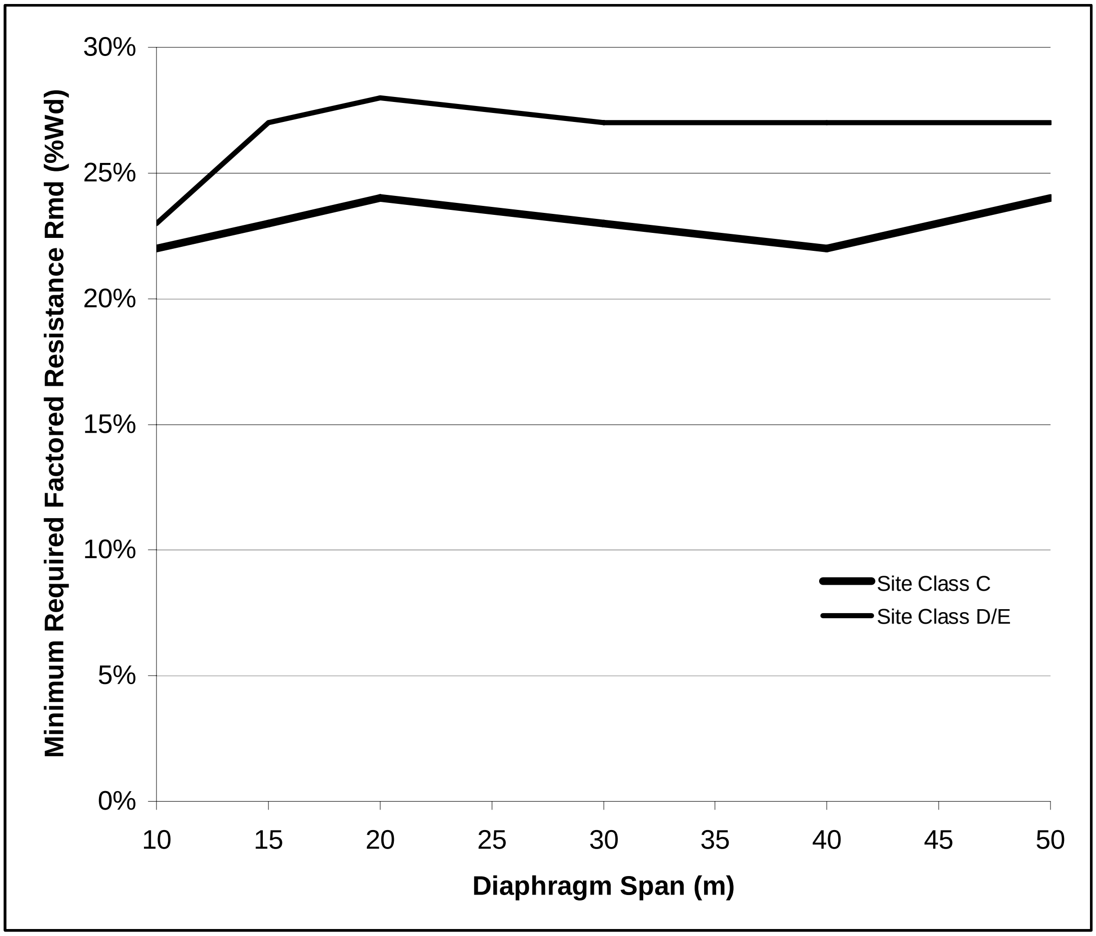


| **Site Class** | *1.0%* | *1.5%* | *2.0%* | *2.5%* | *3.0%* | *4.0%* |
|---|---|---|---|---|---|---|
| *C* | 33% | 22% | 16% | 12% | 10% | 8% |
| *D* | 47% | 25% | 20% | 16% | 13% | 10% |
| *E* | 53% | 29% | 23% | 19% | 16% | 12% |

**Figure 3-1(c)**

*Minimum Required Lateral Factored Resistance* $R_m$ *(%W)*
*Wood Prototype W-1 Blocked OSB/Plywood*
*Seismic Zone 4 (Vancouver)*

Figure 3. Resistance Table for Blocked Plywood Shearwalls in Vancouver.



**D-3 Zone 5**

| Site Class | *10m* | *15m* | *20m* | *30m* | *40m* | *50m* |
|---|---|---|---|---|---|---|
| *C* | 22% | 23% | 24% | 23% | 22% | 24% |
| *D* | 23% | 27% | 28% | 27% | 27% | 27% |
| *E* | 23% | 27% | 28% | 27% | 27% | 27% |

**Figure 10-3(d)**

*Minimum Required Retrofit Factored Resistance* $R_{md}$ *(*$\%W_d$*)*
*Diaphragm Prototype D-3 Steel Deck Type A*
*Seismic Zone 5 (Victoria)*

Figure 4. Resistance Table for Steel Deck Diaphragm in Victoria.

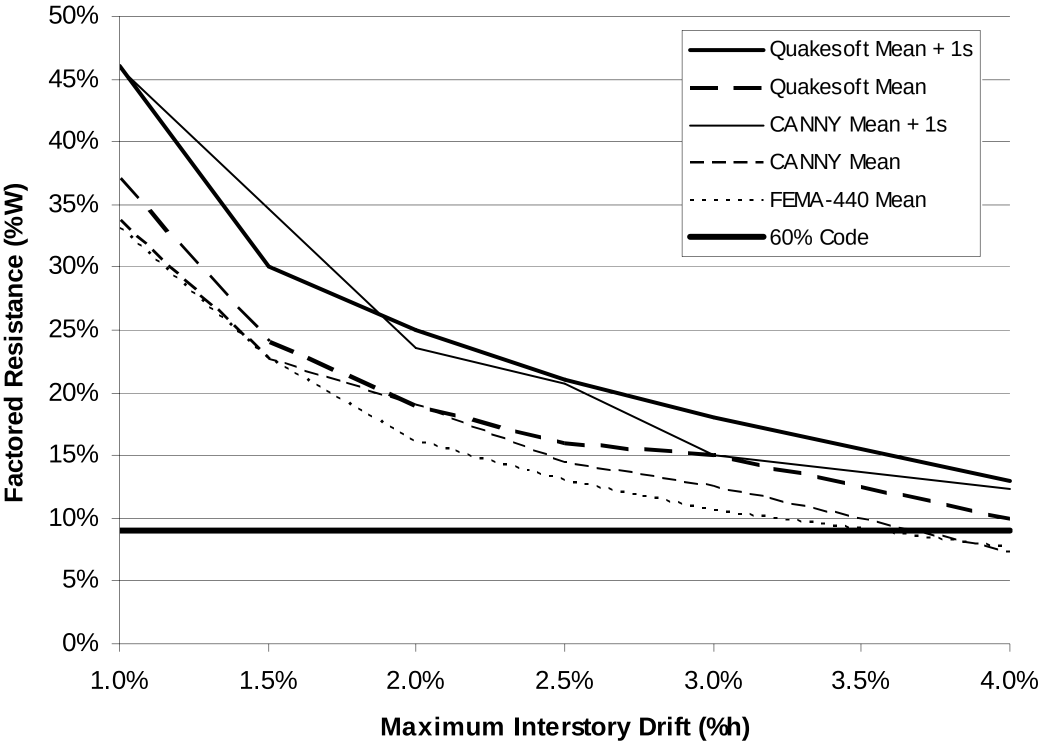


Figure 5. Validation Results for Steel Braced Frames (Tension Only).

## Application of Bridging Guidelines

### Lateral Systems

The minimum seismic performance requirements for a school building in the Bridging Guidelines are: (1) acceptable life safety risk for all LDRSs (2) well defined load path with adequate diaphragm and connection strength; (3) non-LDRS drift compatibility; and (4) adequate restraint of heavy partition walls.

The minimum strength tables given in the Bridging Guidelines allow the engineer to satisfy requirement (1), provided all of the LDRSs do not exceed the Governing Drift Limit (GDL). The GDL is defined in terms of the prescribed Instability Drift Limit (ISDL). The ISDL is the maximum permissible inelastic drift that limits building structural damage to a level that poses no significant risk of local or global collapse of building structural elements. The GDL is a crucial parameter in the evaluation of inelastic deformation performance. The GDL is the lowest ISDL value for the participating LDRSs and the load bearing non-LDRS framing elements. The ISDL values recommended for use in the Bridging Guidelines are shown on Table 1.

The engineer must ensure that the building meets requirements (2) through (4) to qualify to use the minimum strength tables. Guidance is given on height to thickness ratios for out-of-plane clay brck unreinforced masonry walls. Prescriptive measures are given for out-of-plane requirements for concrete masonry and heavy partitions walls.

Load bearing non-LDRS framing elements (e.g. non-ductile concrete columns) must be capable of maintaining their support of vertical load for inelastic building deformations as large as the GDL. These conforming non-LDRS framing elements are deemed drift compatible. The Bridging Guidelines provide a method for estimating the maximum drift that a non-ductile concrete column can accommodate.

The assessment/retrofit procedure involves two steps: 1) the determination if the building meets the assessment level; and 2) if it does not, upgrade the building until it meets the retrofit level (different from the assessment level). The next two sections discuss this process.

The procedure for determining an acceptable level of risk of a building with several LDRS's has the following steps:

1. (1) Identify LDRSs in each orthogonal direction. Determine the factored resistance (Re) of the first story of each LDRS.
2. (2) Calculate the factored resistance ratio Rr (as %W) for each LDRS (in one direction) by dividing the factored resistance Re by the corresponding Rm value (from the resistance tables).
3. (3) Determine total factored resistance ratio (Rrt) by summing all the Rr values.
4. (4) Verify that Rrt equals or exceeds 80% (assessment level). If Rrt is less than 80%, the building will require a structural upgrade.
5. (5) Repeat steps (2)-(4) for the other direction.

If the building needs a retrofit, additional LDRS must be added, or existing ones must be strengthened. Once additional strength to the system has been added, follow the procedure above. If Rrt is less than 100%, the total lateral resistance of building retrofit needs to be further upgraded. If Rrt for a proposed retrofit solution is substantially greater than 100%, the total lateral resistance of the building retrofit can be prudently reduced with the Rrt always equal to or greater than 100%.

Note that once a building has been targeted to be upgraded, it must be upgraded to a higher standard (100%) than the assessment level (80%)

### Combining the Resistance of Different LDRS (Toolbox Method)

One of the major advantages of the Bridging Guidelines is the Toolbox method, a simplified method for combining resistance contributions from mixed lateral systems in a drift-compatible manner. This is a simple, rational method developed in the Bridging Guidelines in recognition that low-rise buildings are often comprised of more than one LDRS. These guidelines represent the minimum factored resistance requirements in a format that permits the engineer to treat each LDRS individually and then combine the LDRSs in a deformation-compatible manner for overall building performance.

An example of the application of the Toolbox method is presented in Figure 6. In this case a two storey building located in Seismic Zone 4 on Site Class C soils is considered. The evaluation will focus on the first storey of the building. The unreinforced clay brick masonry load bearing wall determines the GDL (1.0%) in this case. The building has five LDRSs as illustrated in Figure 6. The first set of calculations checks if a retrofit is required. The existing building requires upgrading because the sum of the Rr (Rrt) is less than 0.8 (0.76 in this case). The first retrofit option is to upgrade both the steel brace and the wood shear wall as illustrated. The second retrofit option is to demolish or isolate the URM clay brick masonry wall, thereby increasing the GDL to 1.5% (governed by concrete masonry wall). Modest upgrading of the wood shear wall now results in an acceptable retrofit solution.

The benefits of the toolbox method are immediately apparent. In a traditional retrofit, the probable drift-compatible choice would be to upgrade the factored resistance of the wood shear wall from 7%W to 35%W. The toolbox method only requires the wood shear wall to be upgraded from 7%W to 9%W, a relatively modest upgrade. By considering the contributions from all drift-compatible LDRSs, the Toolbox method offers highly cost-effective retrofit options when compared with more traditional retrofit options.

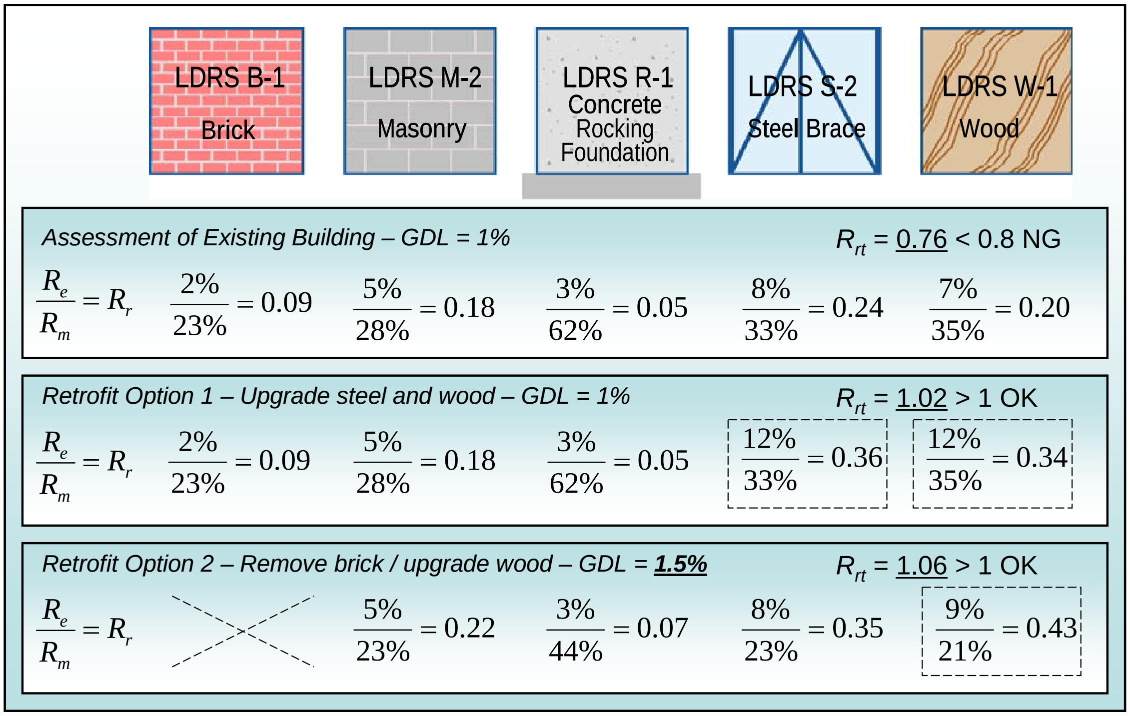


Figure 6. Toolbox Method of Combining Systems.

### Limitations

The Bridging Guidelines are restricted in application to: (1) Low-rise existing buildings (1-3 stories) (2) buildings with a well-defined load path (3) buildings with diaphragms with adequate strength and wall connections (4) buildings with plan eccentricity not greater than 20% in one direction and 10% in the orthogonal direction (5) steel or wood frame buildings with no diaphragm torsional redistribution of inertia forces; and (6) building sites where soil liquefaction is not a significant hazard.

## Future of the Guidelines

The 1st Edition of the Bridging Guidelines was completed in June 2005, and the 2nd Edition completed in the March of 2007. The Technical Guidelines (final version) are slated to be finished in 2010. There are several issues that need to be addressed in the final version.

### Soft Soils Study

Past efforts have shown that scaling ground motions to NHERP levels for soft soils produces extremely high demands when using those scaled motions for non-linear dynamic analysis. The next phase of the project proposes to produce new criteria for scaling ground motions for soft soil sites. This will be done by undertaking an extensive analytical program that investigates the non-linear response of soft soil profiles taken from existing school locations.

### Experimental Testing and Prototypes

Additional experimental testing will be done to generate more accurate backbone/hysteretic curves for existing materials, such as concrete masonry (including infill walls). Testing will also be done on innovative retrofit techniques, to ensure they perform as predicted, and to incorporate them as LDRS prototypes in the Toolbox method. Some examples of this are FRP reinforced shearwalls and sheet metal on steel studs.

### Comprehensive Validation of Toolbox Method

Three dimensional models of buildings with multiple LDRSs in each direction will be analyzed to ensure that the Toolbox method works for even the most extreme cases. In addition, inelastic diaphragms and inelastic LDRSs will be analyzed together to observe the interaction between the to energy dissipating elements.

### Adaptation to Eastern Canada

While the resistance tables are specific to British Columbia, the methodology behind them is universally applicable. The next logical step in the development of the Technical Guidelines is to develop resistance tables for Eastern Canada.

## Closing Remarks

Advanced performance-based seismic engineering solutions are now being introduced into engineering practice in British Columbia. The first application for this evolving seismic engineering technology is the $1.5 billion seismic mitigation program for the province's school buildings. The Bridging Guidelines described in this paper have been developed as a first step in accelerating the use of advanced engineering solutions for life safe and cost-effective earthquake preparedness in British Columbia. The next proposed step in this program is the development of a comprehensive Retrofit Strategies and Guidelines Manual that will refine and expand the scope of the Bridging Guidelines for the upgrading of provincial low-rise school buildings.

## Acknowledgments

We wish to acknowledge the valuable technical contributions of all project team members to the development of the Bridging Guidelines. In particular, we wish to recognize the contribution of the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) in its role of overall project manager and the invaluable critique and feedback provided by the APEGBC Peer Review Committee selected for this project. Special thanks to Mr. John Sherstobitoff of Sandwell Engineering for providing the material for Figure 6.

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