Seismic Retrofit of School Buildings in British Columbia, Canada

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SUMMARY
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 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 being used by engineers to determine retrofit strategies for schools in British Columbia.

Keywords: Performance Based Design, Seismic Retrofit, Probabilistic Seismic Hazard Assessment, Incremental Dynamic Analysis, School Buildings.

1. INTRODUCTION

British Columbia (BC), on the West Coast of Canada is located in a region of moderate to high seismicity. In 2004, the British Columbia Ministry of Education initiated a $1.5 billion seismic mitigation program to make all public elementary and secondary school buildings safe. This seismic safety program is being implemented by the BC Ministry of Education (MOE) in collaboration with the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC). APEGBC has been contracted by MOE 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 low-rise school buildings. This technical development program is now in its eighth year. The initial version of the guideline was released in 2006 (APEGBC, 2006), and has been improved and enhanced since then. The current edition of the guidelines, called Seismic Retrofit Guidelines, 1st Edition, SRG-1, (APEGBC 2011) was released in September of 2011. The second edition of the SRG will be published in the spring of 2013. In undertaking this technical development program, APEGBC contracted the University of British Columbia (UBC) 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 three overall objectives of the SRG are enhanced life safety, cost effective retrofits and user-friendly technical guidelines. The life safety philosophy of these guidelines is enhanced life safety through minimizing the probability of structural collapse by the use of rational performance-based methods of earthquake damage estimation. Cost-effective strategies are achieved by a combination of the development of rational minimum resistance requirements and the qualitative formulation of preferred retrofit methods. The development of these requirements is based on probabilistic nonlinear dynamic incremental analyses using ground motions specific to the three different sources of ground motions in the region: crustal, subcrustal and subduction sources. User-friendly technical guidelines have been developed and presented in the form of pre-determined minimum lateral resistance requirements and a simple-to-use web-based seismic performance analyzer 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. This tool, called "Seismic Analyzer" provides the engineer with immediate, user-friendly access to the large electronic database of analysis results. This format permits the practitioner to capitalize on the benefits of advanced performance-based engineering techniques without subjecting them to undertake sophisticated non-linear time history analyses. Within the context of the seismic upgrading of schools, the immediate retrofit strategy targets the identification of high risk portions of schools that require retrofitting on a first priority basis. For this reason, a school is divided into its component ``blocks` of similar construction and storey height.

This seismic assessment tool incorporated revised design criteria from the 2005 NBCC. Schools included in the survey were those that were designed prior to adoption of the 1992 British Columbia Building Code (BCBC) or equivalent, including any schools that may have been upgraded since 1990. All new schools or additions designed to the newer code were excluded from the survey. Also excluded were schools that have been closed, schools scheduled for replacement or major rejuvenation, and non-enrolling facilities such as board offices and maintenance shops. Over 850 schools located in 37 school districts were assessed over a three-month period. About 750 schools were found to have one or more building components rated at moderate to high risk. The remediation costs for these schools were estimated to be close to $1.5 billion. Considering the high cost estimate for completing this ambitious program, the need for the development of rational, cost-effective retrofit technology, directly applicable to the geological and seismic setting of BC and that recognizes standards of construction practice in the province became an important component of this program.

The performance-based methodology for seismic retrofit of schools that has been developed addresses two major shortcomings in current engineering practice by both providing a rational method for verifying life safety in each school building and by facilitating cost-effective retrofits of buildings founded on firm ground. The three overall objectives of this methodology are enhanced life safety, cost-effective retrofits and user-friendly technical guidelines. Cost-effective strategies are achieved by a combination of the development of rational minimum resistance requirements and the qualitative formulation of preferred retrofit methods. User-friendly technical guidelines are 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 the practitioners to the need to undertake sophisticated non-linear time history analysis.

The principal generic performance objective of the Guidelines is life safety. Damage mitigation and habitability (immediate occupancy) are secondary performance objectives not specifically addressed in the guidelines. In the guidelines, the risk to life safety is managed through a reduction in the probability of catastrophic casualties resulting from structural collapse. The risk to life safety from the failure of heavy partition walls is also included in the guidelines. Non-structural seismic mitigation and general renovation remain in separate programs.

2. METHODOLOGY

2.1 Deformation-based Methodology

The SRG differs from current practice in how the capacity (C) and demand (D) values are used in the seismic engineering process. In contrast to the prescriptive C/D ratio approach of current practice, this new procedure implemented in the SRG determines a probabilistic risk for each block element. This probabilistic risk is the probability that the peak drift (an indicator of damage) in the element will exceed the permitted drift limit over a specified time duration (e.g., 50 years). The methodology differs substantially from the prescriptive code-based approach commonly used in current practice for the seismic upgrading of low-rise buildings. This methodology uses inelastic deformation rather than force, or base shear force, to quantify building performance

The differential movement between floors, or drift, is the key parameter used to define building damage due to lateral shaking. The methodology can be used to perform key steps in the retrofit process: Risk Assessment and Retrofit Design. The Risk Assessment is used to determine if a building does not meet the prescribed performance objective, while the Retrofit Design is used to determine what type of retrofit is the most cost-effective so that the building meets the performance objective. The principal elements of the non-linear performance-based methodology discussed in this paper are:

- Inelastic deformations, rather than forces, are utilized to quantify building performance.
- Probabilistic estimates of exceeding selected maximum deformation levels are utilized for each building system for three potential earthquake sources, crustal, sub-crustal and subduction, including distance from the likely earthquakes and local soil type.
- Nonlinear characteristics are developed for the most prevalent structural systems in the province, as well as new construction systems to be used as retrofits.
- Multiple nonlinear dynamic analyses are performed for each structural system for increasing ground motion intensities in order to establish the probability of maximum deformation exceedance.
- Capability to mix different structural systems in assessing the existing building risk, as well as, combination of existing and new retrofit structural systems.
- An effective way to utilize all available information in assessing the seismic risk of a specific school building and provides the capability of selecting the most efficient retrofit scheme for that building.
- Laboratory test results for various existing and new elements, novel materials and innovative retrofit methods can be readily incorporated as part of the methodology.

2.2 Probable Earthquake Damage

The issue of probable earthquake damage clearly differentiates this methodology from current code-based practice. This methodology uses probable damage rather than probable ground motion as the principal parameter for determining earthquake performance. The force-based probable ground motion approach in the British Columbia code is based on ground shaking with a 2% probability of exceedance in 50 years. This approach has a built-in binary decision-making process. A building either has enough capacity or not enough capacity to resist the prescribed demands.

The probable ground motion approach makes no judgment on the degree to which the building either exceeds or falls short of the minimum strength requirements. In contrast, the probable damage methodology, based on inelastic deformations, considers a wide range of possible ground shaking, from moderate shaking (associated to insignificant damage) to extreme shaking that has a probability of exceedance considerably less than the 2% in 50 years used in the BC code. The approach permits the probability of excessive damage (shear deformation in excess of the drift limit) to be determined for a specified building life (e.g., 50 years) and any conceivable earthquake scenario based on the local seismic hazard data.

2.3 Principal Building Elements

Building components that have a significant influence on the seismic performance of a structure are classified as belonging to one of five categories of principal building elements. These five principal elements have a hierarchy in terms of life safety risk (the first element represents highest relative risk): 1) vertical load-bearing supports; 2) lateral deformation-resisting systems (LDRSs); 3) partition walls rocking out-of-plane; 4) diaphragms; 5) connections.

The most important principal building elements in a heavily damaged building are the vertical load-bearing supports. To prevent a catastrophic collapse, the vertical supports must maintain their load-bearing capacity for the full range of inter-storey drift. The lateral deformation-resisting system (LDRS) is the second most important principal building element. If the support of the vertical load is maintained throughout the duration of shaking, the second collapse-prevention requirement is that the LDRS is sufficiently strong to prevent lateral instability and possible lateral collapse. Many older low-rise buildings have heavy non load-bearing partition walls that are constructed of unreinforced masonry. The life safety concern posed by these walls is localized out-of-plane collapse. Out-of-plane rocking is a good mechanism for dissipating energy provided the maximum out-of-plane movement is restricted to the thickness of the wall.

Excessive deformations in floor and roof diaphragms do not generally constitute a threat to life safety but the severity of earthquake damage can substantially increase with poor diaphragm performance. The engineer needs to use his or her judgment in assessing the life safety implications of inadequate diaphragm performance. For instance, in a wood frame building an inadequate existing roof diaphragm can be upgraded within the maintenance cycle without exposing the building occupants to undue risk. Connections are a key element for continuity of load path from foundations to the roof. The design of connections is generally conservative given the modest premium for installing stronger or more closely spaced connections. Similar to the approach to diaphragm performance, poor existing connections do not automatically have immediate life safety implications.

2.4 Building Prototypes

Prototypes are models which represent a specific form of construction or structural system. The different types of Lateral Deformation Systems (LDRS), diaphragms and unreinforced masonry walls rocking out-of-plane are modeled by a selection of different building prototypes. Each LDRS, diaphragm and URM wall rocking out-of-plane prototype has its defining drift limit, strength backbone curve, hysteretic curve (loading and unloading resistance variation) and damping. Figure 1 below, shows a typical example of the LDRS representation, corresponding backbone curve and hysteresis curve.

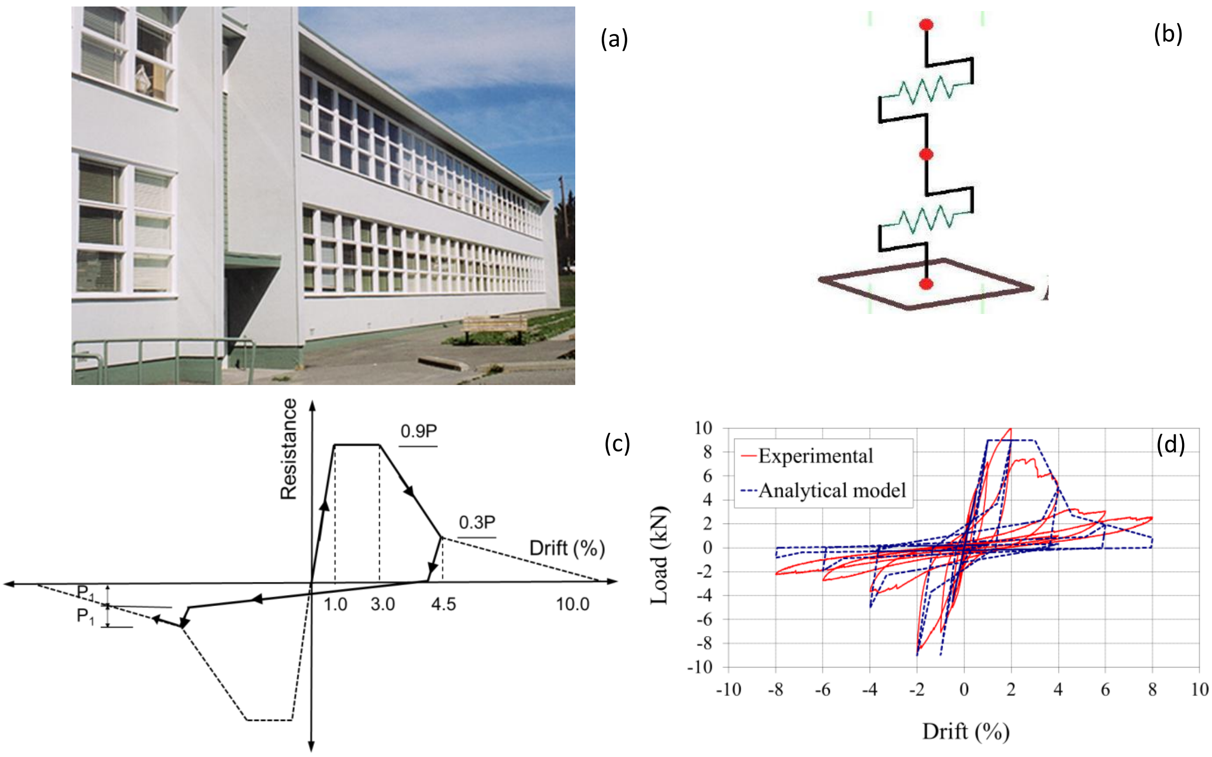

Figure 1. (a) Typical wood school building with blocked OSB / plywood lateral deformation resisting system (b) Analytical model (c) Hysteretic behaviour model (d) Comparison of experimental and analytical model

2.5 Ground Shaking Intensity

Structural velocity is considered as the best indicator of severe structural demands resulting in damage to a structure, as opposed to peak ground acceleration or displacement. The associated ground shaking intensity causing significant structural velocity demands is determined by calculating the average spectral pseudo velocity (PSV) for the period range of interest (see Pina et al. 2010) for details on the period range of interest). The PSV is calculated from the seismic hazard data published for each geographic location. Figure 2 shows the PSV for the Uniform Hazard Spectrum (UHS) for a site class C in Vancouver obtained from the BC code, and it also shows the corresponding PSV for crustal and sub-crustal earthquakes for Vancouver and for subduction earthquakes for Victoria. These spectra are for the 2475 year return period and 5% damping.

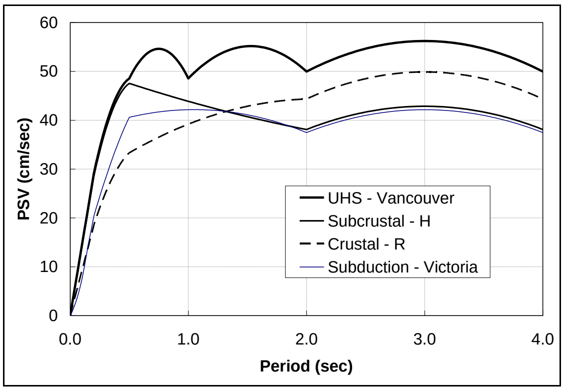

Figure 2. PSV spectra for site class C soil of different earthquake sources for the city of Vancouver (crustal and subcrustal) and Victoria (subduction) for a 2475 year return period earthquake.

2.6 Levels of Ground Shaking

The full range of possible ground shaking is divided into a series of ground shaking increments. All levels of shaking are expressed as a percentage of a benchmark level of shaking. The "100%" intensity level is taken as the benchmark level, and it corresponds to a level of shaking with a 2% probability of exceedance in 50 years. Each ground shaking increment has a range of 10%. For example, the ground shaking increment immediately below the benchmark level of shaking has a level of shaking that ranges from 90% to 100%. For any geographic location, the full range of ground shaking varies from the 30% to 250% level of benchmark shaking.

2.7 Seismic Hazard

The south-west corner of British Columbia, where about 80% of the population of the province lives, has significant hazard contributions from crustal, subcrustal and subduction earthquakes. Construction in BC is regulated by the provincial design code, which is based on the National Building Code of Canada, NBCC, (Canadian Commission on Building and Fire Codes, 2005). The design response spectrum in the NBCC is based on a Uniform Hazard Spectrum (UHS) that envelops the spectral acceleration values from all three earthquake types. To reduce the conservatism of this code-based definition of the seismic hazard data is de-aggregated by considering the seismic hazard data for each type of earthquake separately. Seismic hazard data for each type of earthquake was generated using the commercially available computer program EZ-RISK (Risk Engineering, 2008). The analysis results have been verified with reference to the open source data provided by the Geological Survey of Canada, GSC (Adams and Halchuk, 2003).

2.8 Ground Motion Suites

Ground motion at any geographic location is modeled by three ground motion suites of ten ground motions per suite - one suite for each of crustal, sub-crustal and subduction earthquakes (Pina et al.

2010c). The crustal and sub-crustal suites of ground motions have been scaled for Vancouver's benchmark 100% level of shaking. The subduction suite of ground motions has been scaled to Victoria's 100% level of shaking.

2.9 Soil Amplification

Site Class C (firm ground – very dense sand or soft rock) is the reference (so called in Code) site classification used in this methodology. All soils softer than firm ground are treated as one category (Site Class D / E / F) that amplifies the level of shaking at the underside of the foundations beyond that for Site Class C. The soil amplification effects are introduced in the analysis through the use of an Equivalent Intensity Factor (EIF) that exceeds unity for building sites in the Site Class D / E / F category (Pina et al. 2010c).

2.10 Quantifying Probable Damage

Building performance is quantified by analyzing a given building in a given location for a range of levels of shaking. The results of the analyses are used to determine the probability of excessive damage peak drift in excess of the drift limit, expressed as a percentage. Each level of shaking increment is assigned a calculated probability of occurrence based on the latest seismic hazard data published for that geographic location. Within each level of shaking increment, the probability of excessive damage is calculated by analyzing the building for the set of ground motions scaled for the average level of shaking. The total probability of excessive damage is calculated by summing the probability of excessive damage contributions for all level of shaking increments. This probability of excessive damage is the prime basis for measuring and assessing earthquake damage and relating it to life safety.

The Design Drift Limit (DDL) is the maximum drift that can be used in retrofit design or seismic assessment. Qualitatively this drift limit represents a damage level in a building that is “life-safe”. The life-safety performance objective is defined by two main criteria:

1. Probability of Design Drift Exceedance (PDE) of 2% in 50 years.
2. Conditional Probability of Drift Exceedance (CPDE) of 25% or less for Near Collapse Conditions at 100% of the code ground motion (2,475 year return period).

Drift exceedance is simply drift that exceeds a specified drift limit. The maximum PDE values for each of the principal building elements are provided to the designers, and can be used in both the risk assessment and retrofit design phases. A detailed explanation of how this is done is presented by (Pina, et al. 2010a).

This methodology is based on an incremental probabilistic non-linear dynamic analysis (IPNLDA) or incremental dynamic analysis (IDA) as it is more commonly called (Vamvatsikos and Cornell, 2001). Common types of low-rise school buildings have been analyzed for the full range of ground shaking in all regions of the province to generate a large database of analysis results. This involves taking a given prototype model (typically inelastic and non-linear), subjecting it to suites of ground motions of varying intensity, and then repeating for a range of different resistances for that prototype. Each suite of records represents a particular earthquake hazard (i.e. crustal, subcrustal and subduction), to which a particular probability is attached. Each varying level of intensity represents ground motions of different magnitudes (or return periods) and also has a probability attached. For each combination of resistance, ground motion intensity and earthquake hazard type, a suite of motions is used to perform non-linear dynamic analysis. From this run a CPDE is calculated as the percentage of runs where the design drift limit was exceeded divided by the total number of runs.

The PDE is calculated by multiplying the individual CPDE by their probability of occurrence (based on data from the Canadian Geological Survey) and summing them up over all ground motion intensities and earthquake hazards. This procedure is done incrementally (i.e. for a wide range of resistances) so that relationship between PDE and resistance can be determined.

The appropriate design drift level to use for the exceedance check was determined by examining the CPDE (measured at the design drift limit) at the 2500 year (100% code) year level. The design drift was set such that the required resistance for the 2% PDE did not result in a CPDE in excess of 25%. This method ensured that there was a rational basis for the 2% PDE and that all types of retrofit construction will have the same level of safety to the code level ground motion. The procedure to compute the DDL, PDE and CPDE is illustrated in Figure 3 below.

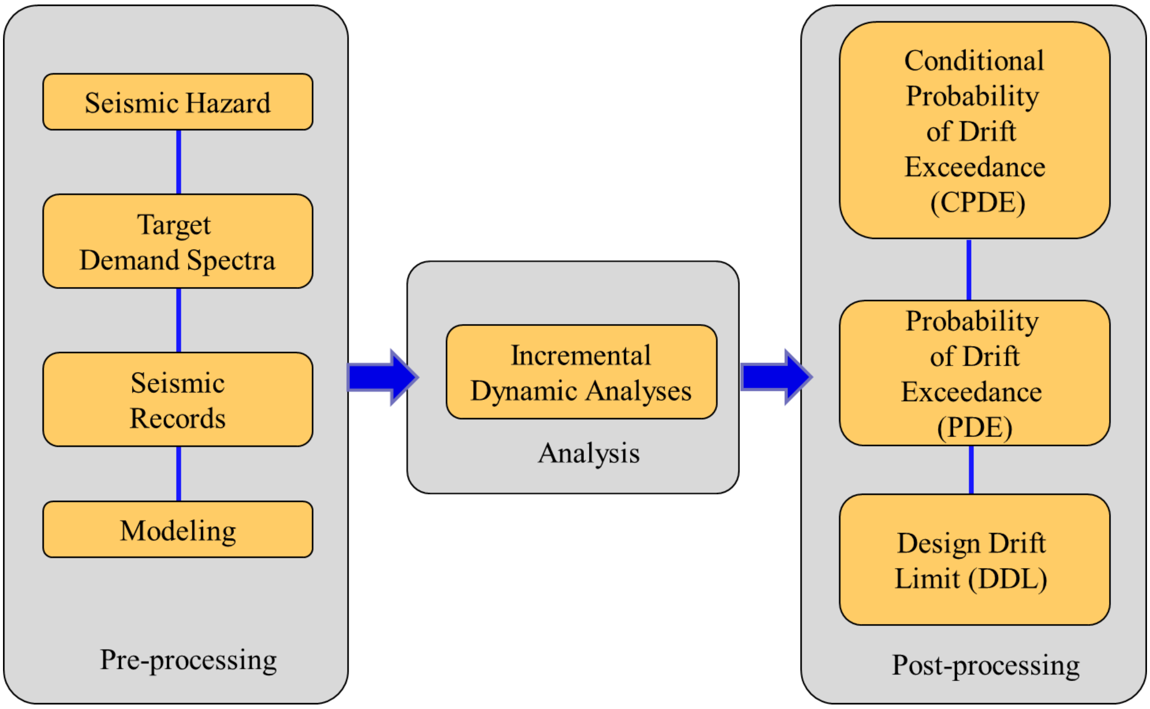

Figure 2. Procedure to calculate PDE and DDL

2.11 Seismic Performance Analyzer (Analyzer)

The Analyzer is the principal analytical tool of this methodology. This web-based tool provides the engineer access to a highly advanced, peer-reviewed analytical database without requiring the engineer to be experienced in the use of nonlinear dynamic analysis techniques. The Analyzer permits the engineer to quickly analyze the three principal building elements that have analytically complex behaviour. These three principal building elements are LDRSs, walls rocking out-of-plane and diaphragms. For each of these three building elements, the Analyzer performs a risk assessment or a retrofit design (either basic or detailed). After making the basic parametric selections (input data), the engineer clicks on the Analysis button and the analysis results are instantly displayed.

For risk assessment, the Analyzer provides the engineer with an estimate of the maximum risk for (a) the lateral deformation-resisting system (single LDRS or group of LDRSs), (b) a particular URM wall rocking out-of-plane or (c) a diaphragm that provides out-of-plane support for exterior or interior walls. For retrofit design, the Analyzer provides the engineer with an estimate of the minimum required factored resistance for a particular LDRS or a wood or steel deck diaphragm. Figure 4 shows a sample snapshot of the graphical interface of the Analyzer for risk assessment and retrofit design.

The structural system of a school block is modelled in an analysis by a series of block prototypes to represent the principal building elements. The principal block elements are: a) the lateral deformation-resisting system (LDRS) elements; b) vertical load-bearing supports; c) URM walls rocking out-of-plane (where applicable); d) floor diaphragms; and e) foundations.

A variety of prototypes representing the above elements are represented in the Analyzer database. The parametric variations included in the Analyzer database include: custom seismicity for all school districts with significant seismicity; Site Class C and Site Class D soil types; various LDRS, URM walls rocking out-of-plane and diaphragm prototypes; range of Design Drift Limits; range of clear storey heights; range of LDRS and diaphragm factored resistances; URM wall parameters (height, thickness, surcharge, load-bearing or partition); diaphragm parameters (span, lateral displacement limits).

Figure 4. Screenshot of Seismic Performance Analyzer for Risk Assessment and Retrofit Design options for a Wood Frame LDRS system

2.12 Toolbox Method

The Toolbox is one of the unique features of the retrofit methodology. The Toolbox permits the engineer to combine the contributions from different LDRSs in performing either a risk assessment or a retrofit design. The principal technical consideration is the need for all included structural systems and components to generate their lateral resistance in a drift-compatible manner. The Toolbox Method is the generation of LDRS lateral resistance in a drift-compatible manner. For a group of LDRSs, the drift limit for the assembly of LDRSs is the lowest drift limit of the participating LDRSs of the structure being considered. This approach permits the engineer to use all materials, new and existing, in formulating a cost-effective risk assessment or retrofit design (White, et al., 2007). Each system or component is relied on to generate resistance up to this governing deformation limit. Conceptually, the Toolbox uses a simplified and modestly conservative approach to determine the contribution of each structural system or component to the total lateral resistance. Each contribution is calculated as a percentage of the total inertia mass on the basis of its lateral resistance capacity at the governing deformation limit. These percentage contributions are then totalled to determine the overall building response capacity. If the total capacity equals or exceeds 100% of the required capacity, the risk assessment or the retrofit design is deemed to be satisfactory. Conversely, if the total capacity is less than 100% of the required capacity, the building's risk assessment or retrofit design is deemed to be deficient.

2.13 Implementation of Methodology

The decision on whether or not a building block needs to be retrofitted is based on the estimation of the Capacity of the structure to satisfy the Demands expected at the site of the building. The engineer calculates the capacity (factored resistance) of the block elements in accordance with best current design practice in Canada. The engineer then uses the Analyzer to determine the demand for each LDRS in the block. To undertake a comprehensive seismic risk assessment or a retrofit design, the engineer follows the requirements of the Guidelines and Commentary using the capacity and demand values determined. If more than one LDRS is being considered, the Toolbox method can be used to determine these values. For acceptable performance, the probabilistic risk for each block element must not exceed a pre-determined drift limit. If this limit is exceeded, the block element requires retrofitting.

3.0 CLOSING REMARKS

The methodology described in this paper represents a major advance in seismic engineering practice in British Columbia. The principal features of this methodology are:

- insight into the mechanics of earthquake damage;
- ability to mitigate earthquake damage to the performance requirements of the owner;
- ability of quantify benefit/cost comparisons easily and quickly for a range of seismic upgrading options;
- deaggregated tri-hazard risk estimation;
- rational quantitative method of assigning risk;
- full range of levels of shaking considered (probable damage methodology);
- probabilistic measurement of risk and performance;
- incremental probabilistic non-linear dynamic analysis;
- large electronic database of analysis results for the use of structural engineers engaged to seismically upgrade school buildings; and
- ability to combine lateral resistance contributions for a range of new and existing LDRSs.

The performance-based methodology implemented in this project represents a very innovative approach to seismic retrofit which can have wide reaching positive influence on seismic design practice not only in British Columbia but all over the world. A unique feature of this methodology is that the engineers are relieved from performing sophisticated nonlinear analysis for individual buildings in order to benefit from the advantages of probabilistic performance-based design approach. They can then utilize their conventional engineering knowledge to assess and retrofit structures and to use the Analyzer to provide them with the few parameters that they need to achieve their design. This novel approach can be adopted and readily modified for low-rise buildings other than schools and for a wide range of performance objectives from immediate occupancy to collapse prevention.

By judiciously implementing of the performance-based seismic mitigation program it is estimated that savings of at least 10% to 40% of the estimated construction costs using the traditional code-based approach can be achieved. As the NBCC is explicitly written for the design of new buildings, it explicitly notes that strictly applying the prescriptive requirements of the NBCC to existing buildings is inappropriate, and states that, “alternate solutions are required”. An alternate solution permitted by the Code is a Non-Linear Dynamic Analysis (NLDA). The NLDA forms the basis of the Seismic Retrofit Guidelines as created by APEGBC and UBC. This analysis is sophisticated, as it allows for the inclusion of specific BC soil conditions and seismological anomalies. It is also more efficient and appropriate, as it recognizes and incorporates the material types and geometrics used in existing BC public schools. The guidelines therefore allow for the use of existing building elements to contribute to earthquake resistance of the building, which can minimize or eliminate the need for new elements to be included during a retrofit.

The Toolbox Method permits a retrofit design to be fine-tuned. The composition of the participating structural systems and components for a retrofit design can be strategically considered. An existing structural system or component with a low drift limit and a small contribution to the overall building performance can be ignored in the analysis, in many cases, provided that the vertical support is maintained in its absence. This isolation of the more vulnerable structural systems or components from the better ones will result in a higher governing deformation limit. This process can be used to quickly determine the most effective combination of participating structural systems for the retrofit design.

ACKNOWLEDGEMENTS

The development of the unique methodology described in this paper is the result of a highly supportive and collaborative partnership of the following contributors: the British Columbia Ministry of Education; the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC); the University of British Columbia; the APEGBC Structural Peer Review Committee (BC engineers); and the APEGBC External Peer Review committee (California engineers). The authors wish to highlight the contribution of their California colleagues: Dr. Farzad Naeim, Dr. Michael Mehrain and Dr. Robert Hanson, who have provided invaluable guidance to this project in their capacity as members of the External Peer Review committee.

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