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PERFORMANCE-BASED APPROACH FOR SEISMIC RETROFIT OF SCHOOLS IN BRITISH COLUMBIA

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

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 sixth year, with the third edition of the technical guidelines to be published in the spring of 2010. In undertaking this technical development program, APEGBC contracted the University of British Columbia (UBC) to draft the performance-based technical guidelines based

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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 guidelines 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 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. The calculator 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.

Background and development of retrofit methodology

In 2004 the Ministry of Education undertook an assessment of existing schools located in high-risk seismic zones of the Province to determine the potential risk of structural damage or failure that could potentially result from a significant seismic event. This work was conducted in partnership with school districts and with the assistance of the APEGBC using traditional risk assessment methods based on technology developed in the 1980's. School districts were selected for assessments based on seismic hazard maps published in the 1990 National Building Code of Canada (NBCC). Because of the well-known limitations of this assessment tool, a new, more rational assessment tool was developed by UBC and APEGBC.

This seismic assessment tool incorporated revised design criteria from the 2005 NBCC[3]. 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.

Traditional assessment methodologies tend to underestimate or overestimate risk because engineers use a combination of a California-based publications and the building code. The National Research Council of Canada also has some guidelines but they rely on the building code approach. The building code is intended for the design of new buildings, not updating old ones, and therefore is an awkward and conservative tool to use. 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.

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. 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.

Performance-based seismic engineering is in its infancy in British Columbia and Canada. The 2005 edition of the National Building Code of Canada states overall performance objectives but its technical provisions are mostly based on the traditional equivalent static force method or elastic dynamic analysis. The Guidelines represent a major advance in translating sophisticated performance-based seismic engineering analysis into practical, user-friendly rational design requirements. 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 the governing drift limit. 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.

Methodology

The principal elements of the non-linear performance-based methodology discussed in this paper are described in this section.

Deformation-based Methodology: 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.

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.

Performance Objective: As agreed upon with the BC Ministry of Education, life safety is the sole performance objective considered in this methodology for the seismic upgrading of low-rise school buildings.

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. Many connections can be upgraded within the maintenance cycle without substantially increasing the life safety risk.

Building Prototypes: The different types of LDRSs, 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.

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.

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.

Quantifying Probable Damage: 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.

Probability of Drift Exceedance (PDE): The probability of excessive damage is defined as the Probability of Drift Exceedance (PDE). 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 companion paper included in the conference proceedings provides a detailed explanation of how this is done (Pina, et al, 2010a)

Rate of Drift Exceedance (RDE): The second important parameter for checking a retrofit design is the Rate of Drift Exceedance (RDE). For a chosen retrofit design, the probability of drift exceedance at the 100% level of shaking must not exceed prescribed specified limits. For example, partition walls rocking out-of-plane must have a RDE value at the 100% level of shaking not greater than 10% (10% maximum collapse rate).

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).

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.

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).

Incremental Dynamic Analysis: 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. These results are made available to engineers assessing and retrofitting school buildings through the use of an electronic interface called the ***Seismic Performance Calculator***.

The basic steps in the IPNLDA for the seismic risk assessment or retrofit design of a particular school building in a given geographic location are as follows:

Step 1 – Scaling of Ground Motions for Seismicity. The three suites of ground motions (one suite for each earthquake type) are scaled for the local seismicity.
Step 2 – Site Class C Analysis. The building prototype is analyzed for each earthquake type and for each level of shaking in 10% level of shaking increments from 30% level of shaking to 250% level of shaking.
Step 3 – Soil Amplification. The Site Class C analysis results are modified by an Equivalent Intensity Factor (EIF), where applicable, for a site that falls into the Site Class D / E / F category.
Step 4 – PDE and RDE. The PDE value is determined by the Seismic Performance Calculator, described below for a given building and geographic location by the cumulative risk calculation process for each level of shaking increment. The Calculator also determines the RDE value at the 100% level of shaking for a retrofit design check.
Step 5 – Risk Assessment or Retrofit Decision Making. The above PDE and RDE values are used to assess an existing building or check a proposed retrofit design.

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 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).

Seismic Performance Calculator (Calculator): The Calculator is the principal analytical tool of this methodology. The 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 Calculator 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 (refer to Figure 1). For each of these three building elements, the Calculator 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.

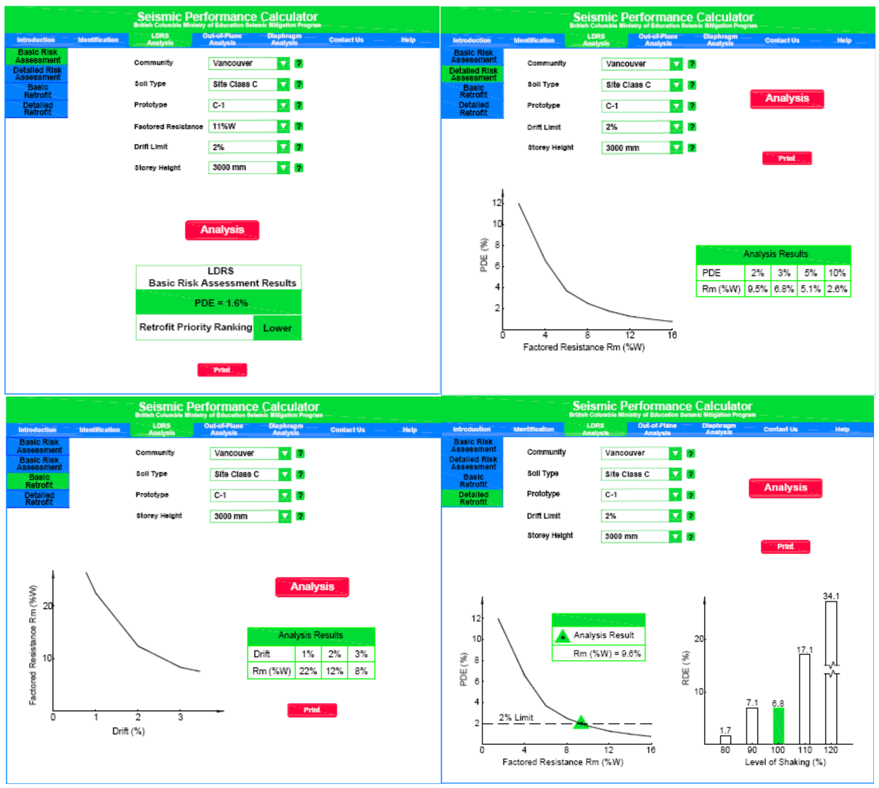

Figure 1. Seismic performance calculator snapshots at basic risk assessment, detailed risk assessment, basic retrofit and detailed retrofit options of LDRS systems

Summary

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.

Conclusions

The methodology has the added advantage that it has immediate application to other types of building infrastructure (hospitals, utilities, government and private industry) in both British Columbia and, through adaptation, to other seismically active regions in Canada. It permits the engineer, in his or her capacity as the engineer-of-record, to initiate a meaningful and quantitative discussion with the building owner on a range of retrofit options for a building. This conversation with the building owner is within the context of building damage rather than the more abstract concept of a ground motion threshold.

As the NBCC is explicitly written for the design of new buildings, it explicitly notes that strictly applying the prescriptive requirements of the Code 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. 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.

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