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PERFORMANCE-BASED SEISMIC ASSESSMENT AND RETROFIT OF MID-RISE BUILDINGS

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ABSTRACT: The Province of British Columbia (B.C.), which is located in a region with a high risk of significant seismic activity along the West Coast of Canada, has implemented a program to mitigate the seismic risk for over 750 provincial school buildings. In order to provide a cost-effective tool for seismic assessment and retrofit of these buildings, a state-of-the-art probabilistic performance-based methodology based on nonlinear dynamic incremental analyses has been developed. The latest implementation of this methodology: a set of guidelines called the *Seismic Retrofit Guidelines 2nd Edition (SRG2)*, was issued in 2013 and includes provisions to assess and retrofit mid-rise university and college buildings belonging to the British Columbia Ministry of Advanced Education (MOAE).

To implement this performance-based methodology for mid-rise buildings requires the use of nonlinear analyses of more sophisticated building models compared to low-rise buildings. This methodology also demands significant computational capabilities in order to complete all the parametric analyses necessary to define the seismic risk of these structures. Due to these factors, the original SRG methodology was adapted to develop a unique set of guidelines specifically for the performance-based assessment and retrofit of mid-rise concrete shearwall buildings. Also developed for use with the guidelines is a high-performance tool that can be used for the rapid evaluation of the seismic risk of these buildings. This tool along with the method developed in this paper allows engineers to benefit from the advantages of probabilistic performance-based design by simplifying and expediting the process of performing sophisticated incremental nonlinear analysis.

1. Introduction

The Ministry of Education of British Columbia (MOE) is currently implementing state-of-the-art guidelines for the seismic assessment and retrofit of over 750 provincial schools. The first edition of the “Seismic Retrofit Guidelines (SRG)” was issued in 2011 (APEGBC, 2011). These guidelines presented a novel performance-based design methodology to provide cost and time efficient seismic remediation measures for the extensive number of building that required assessment. A web-based seismic performance tool: *The Seismic Performance Analyzer (Analyzer I)*, was developed as a companion to the Guidelines. *Analyzer I* provides users access to a database of analyzed and processed incremental nonlinear dynamic analysis (INDA) results. This relieves engineers from performing sophisticated nonlinear analysis for individual buildings while still obtaining the advantages of a probabilistic performance-based design

(PBD) approach.

The BC Ministry of Advanced Education (MOAE) is adopting these procedures for their mid-rise advanced education buildings. “The Seismic Retrofit Guidelines 2nd Edition (SRG2)” (APEG, 2013) were introduced in 2013 and contain new provisions for the assessment and retrofit of mid-rise buildings in B.C. The same methodology used for low-rise buildings has been adopted for mid-rise buildings, with a significant difference in that mid-rise buildings are highly variable and cannot easily be categorized in databases, like low-rise buildings had been with the *Analyzer I*. Consequentially, mid-rise buildings require the use of individual nonlinear analyses of more sophisticated models for performance-based seismic analysis. Significant computational capabilities and time are required to perform these analyses in a reasonably time efficient manner.

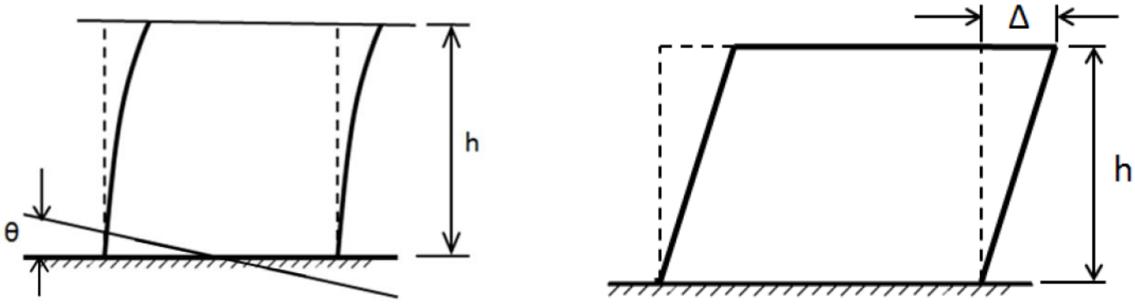
This paper describes how these limitations were overcome in the development of a web-based tool for performance-based seismic assessment and retrofit of mid-rise buildings by taking full advantage of high performance computing (HPC). This tool provides engineers web-based access to conduct extensive nonlinear dynamic analysis of mid-rise buildings under suites of earthquakes of various intensities in a fast and computationally efficient manner. Parallel computing is utilized to expedite the process of conducting the required analyses, and cloud centers provide an elastic computational platform users can access through the internet rather than through local servers. When properly implemented, this approach is a cost-effective way of conducting a great variety of structural analyses of mid-rise buildings in a fraction of the time it would take if these analyses were to be conducted using traditional methods. It also relieves engineers from the complicated and time-consuming post processing of INDA results and obtaining the relevant information.

2. Performance-based Seismic Assessment and Retrofit of Mid-rise Buildings

PBD utilizes sophisticated structural models and nonlinear time history analyses to assess the probabilistic performance of the structure subjected to seismically induced loads. Compared to traditional force-based methods, in which design forces are estimated based on the degree of ductility expected in the structure, PBD can provide much more cost efficient solutions and much more accurate insight into the behavior of the structure during a seismic event (Ghobarah, 2001; Priestley, 2000; Wen, 2001).

2.1. Deformation-based Methodology

One of the key concepts of the SRG2 methodology is that deformations are used to estimate the risk level of a structure. While lateral strength certainly affects the dynamic response of a structure, it is the inelastic deformation levels that govern the damage induced in a structure and are used to set decision limits. This is quite different to force-based methods, typical of design codes, in which pseudo-static lateral forces are applied to the structure in order to design members. SRG2 utilizes interstory drift levels and plastic rotations to quantify the performance of mid-rise structures, as illustrated in Fig. 1.



(a) **(b)**

Fig. 1 – (a) Plastic Hinge Rotation (θ) and (b) Storey Drift (Δ) in a Shearwall

2.2. Incremental Nonlinear Dynamic Analysis (INDA)

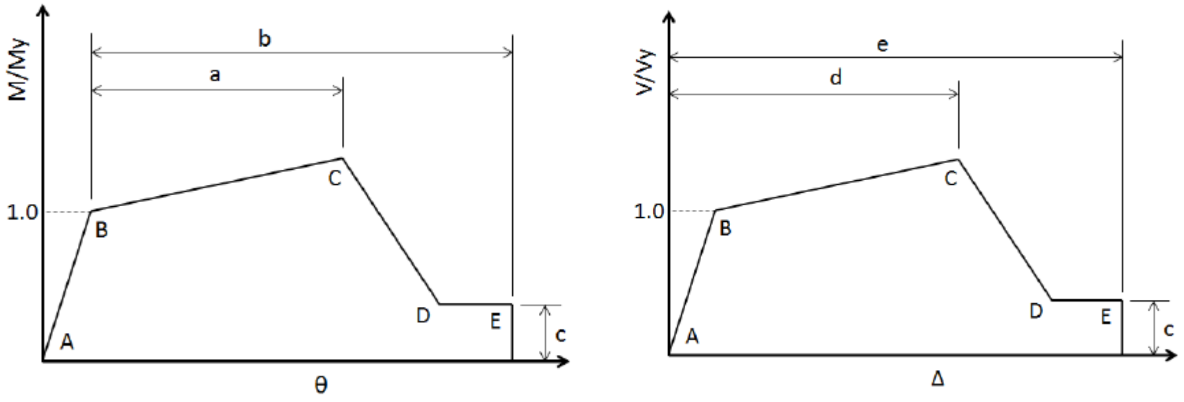
In SRG2, the seismic risk of a structure is performed utilizing INDA (Vamvatsikos and Cornell, 2002). The INDA comprises 30 different ground motion records from the three types of seismic events possible in British Columbia: crustal, subcrustal, and subduction earthquakes. The three hazards are analyzed separately and hazard data from the Canadian Geological Survey is used to combine the results based on the probability of occurrence of each type of event.

The INDA involves scaling each of the ground motions in 10% increments from 10% to 250% of the code based spectral values (2% in 50 year probability of exceedance) for the considered location. Additionally, the site conditions are also considered by amplifying the demands on structures located on softer soils. This method gives insight into the probabilistic performance of the structure being considered, yet requires an extremely large number of analyses to gain valuable information.

2.3. Nonlinear Models

The SRG2 performance-based methodology requires much more detailed nonlinear models compared to the more simple elastic models which can be used in force-based methods. PBD of a structure requires the knowledge of the elastic and inelastic response of the structure, which allows for the modeling of the post-yielding behavior of the structure. This allows the entire response of the structure to be captured when subjected to significant ground excitations.

To expedite the INDA process, concentrated plasticity elements are used in the modeling of mid-rise buildings. These elements can model inelastic shear deformation as well as rotational deformation. When placed at multiple levels in a building, these elements can capture yielding over the height of a structure. Nonlinear rotational springs can also be used to model soil-structure interaction. SRG2 provisions provide guidelines for developing the linear (i.e. initial stiffness) and nonlinear properties (i.e. backbone curves) of flexural and shear controlled concrete shearwalls. Fig. 2 presents the typical moment-rotation and force-deformation backbone curves used for modeling concrete shearwalls buildings in SRG2.



(a) **(b)**

Fig. 2 – SRG2 General Backbone Curves for (a) Flexure- and (b) Shear-Controlled Concrete Shearwalls

2.4. Performance Measures

SRG2 uses two measures to determine the performance of mid-rise structures: 1) The Probability of Drift (or plastic Rotation) Exceedance (PDE or PRE); and 2) The Conditional Probability of Drift (or plastic Rotation) Exceedance (CPDE or CPRE). The PDE is the probability that a Governing Drift (or plastic Rotation) Limit (GDL or GRL) will be exceeded in a 50 year period, considering all possible earthquake sources and all possible levels of shaking. The GDL and GRL are deformation limits selected to provide life safety performance for all components in a structure (all components of the lateral drift resisting system and gravity resisting system). SRG2 provides guidance in determine these limits for different components in concrete mid-rise buildings, such as walls and columns, based on their reinforcement and loading.

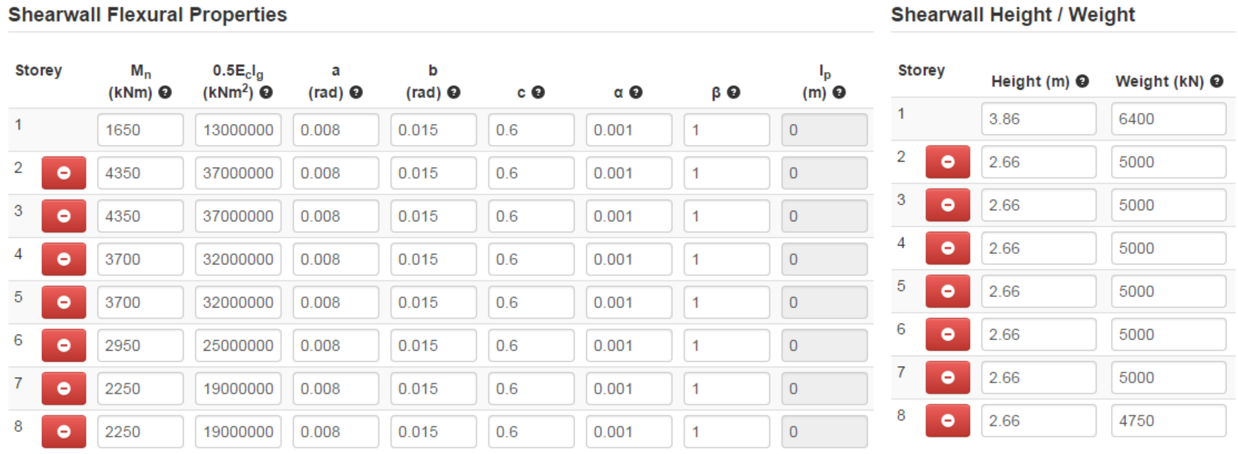
The CPDE and CPRE are deterministic checks on the plastic deformations of the structure when considering a specified shaking level (typically a code shaking level, i.e. 2% in 50 years). CPDE and CPREs are limited to 25% probability of exceedance at a Conditional Drift (or plastic Rotation) Limit (CDL and CRL). The CDL and CRL must be met for all components in the buildings, but are defined only for a collapse-prevention deformation limit. The purpose of the CPDE and CPRE are to ensure a suitable factor against collapse at a specified shaking level, while the PDE and PRE ensure adequate performance of a structure over a 50 year period, considering all possible earthquake scenarios.

3. High Performance Computing Platform

In the SRG2 methodology, each complete INDA requires 750 complete nonlinear time history analyses (three earthquake sources times 10 records for each source times 25 scaling levels). These analyses would be nearly impossible to complete in a reasonable amount of time using sequential computing methods. In order to simplify and expedite the process of INDA for the assessment of BC mid-rise school buildings, a tool, referred to as *The Seismic Performance Analyzer II (Analyzer II)*, was developed. *Analyzer II* utilizes the structural analysis software CANNY (Kanning, 1996) to perform INDA on simple building models. In order to expedite the required nonlinear time history analyses, parallel computing methods were utilized to increase the speed of the analyses, and a cloud computing framework was developed so the user could remotely access cloud servers to conduct the analyses rather than rely on their local hardware.

Users of *Analyzer II* are able to build and submit models on a website, available from any internet connected device. The main role of this website is to provide users with an intuitive and easy-to-use interface, to be used along with SRG2 guidelines, for developing nonlinear models, submitting projects, tracking submitted projects, and rendering graphical results both for online viewing and printing. *Analyzer II* was developed using parallel computing which allows the required analyses to be run in parallel, drastically reducing the computation time. This framework allows the analyses to be run extremely quickly regardless of the processing power of the user's local machine, and does not tie up the user's local hardware to process and store their analysis results. *Analyzer II* is also innovative in the way it relieves engineers of performing and analyzing the results of INDAs, which are typically too time consuming for most projects.

Analyzer II can be used to model walls with varying linear and nonlinear shear and flexural properties over their height. Fig. 3 shows a screenshot of the input page for the Shearwall Flexural Properties and Shearwall Height / Weight for one wall. Different properties can be assigned to each storey, which should be based on the reinforcement and loading of each individual storey according to SRG2 guidelines.



Shearwall Flexural Properties

Storey		M_n (kNm)	$0.5E_cI_g$ (kNm^2)	a (rad)	b (rad)	c	α	β	l_p (m)
1		1650	13000000	0.008	0.015	0.6	0.001	1	0
2	⊖	4350	37000000	0.008	0.015	0.6	0.001	1	0
3	⊖	4350	37000000	0.008	0.015	0.6	0.001	1	0
4	⊖	3700	32000000	0.008	0.015	0.6	0.001	1	0
5	⊖	3700	32000000	0.008	0.015	0.6	0.001	1	0
6	⊖	2950	25000000	0.008	0.015	0.6	0.001	1	0
7	⊖	2250	19000000	0.008	0.015	0.6	0.001	1	0
8	⊖	2250	19000000	0.008	0.015	0.6	0.001	1	0

Shearwall Height / Weight

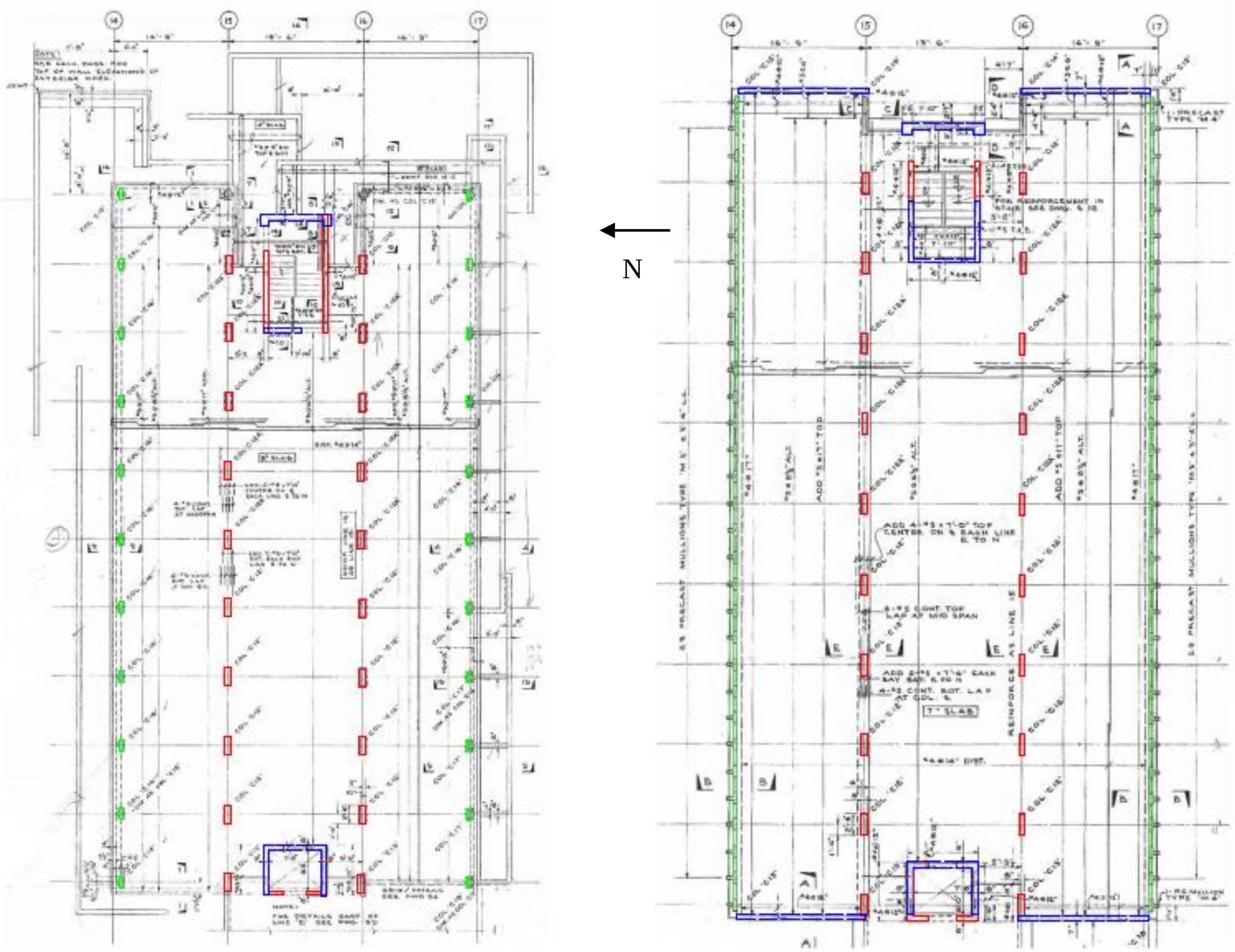
Storey		Height (m)	Weight (kN)
1		3.86	6400
2	⊖	2.66	5000
3	⊖	2.66	5000
4	⊖	2.66	5000
5	⊖	2.66	5000
6	⊖	2.66	5000
7	⊖	2.66	5000
8	⊖	2.66	4750

Fig. 3 – *Analyzer II* Input Screenshot

4. Mid-rise Building Example

To exemplify the application of the SRG2 mid-rise building guidelines, a 9-storey concrete shearwall office building is considered. The LDRS of this structure comprises two continuous concrete shear walls up the height of the building (an elevator core wall and stair core wall), four exterior shearwalls in the North-South direction which are discontinuous at the first and top storey, interior columns which act primarily in the East-West direction, and an East-West exterior moment frame in the first storey. The non-LDRS Load-bearing Supports (VLS) comprises interior columns over the height of the building and exterior precast mullions in the upper stories. The 9th storey penthouse comprises a steel deck roof supported by steel beams and columns and was added to the tower at a later time. This storey was not considered in this analysis since it was newer and had little effect on the behavior and performance of the tower. The LDRS in the North-South and East-West directions are illustrated in Fig. 4, respectively. LDRS components considered to act in the North-South direction are highlighted in dashed blue, LDRS considered in the East-West direction are highlighted in red, while VLS components are outlined in green.

Because this is a busy office building, it is key that the building remains operable during any retrofit addition. Thus, only exterior additions to the building are viable solutions, should remediation be required.



(a)

(b)

Fig. 4 – Example Building Floor Plan with LDRS and VLS Components Considered in Each Direction for (a) Ground Level and (b) a Typical Storey

4.1. Performance Criteria

For this example, the structure is to be assessed for a medium seismic risk. The requirements for medium seismic risk are summarized in Table 1. Note, that for low seismic risk, which is the usual objective, PDE and PRE should be less than 5% and the CPDE and CPRE should be less than 25% at a code level (2% in 50 year) ground motion shaking level.

Table 1 – Life Safety and Collapse Prevention Requirements for Medium Seismic Risk

Life Safety	Collapse Prevention
PDE < 5%	CPDE < 25% for 5% in 50 year ground motion
PRE < 5%	CPRE < 25% for 5% in 50 year ground motion

Table 2 summarizes the deformation limits selected according to the SRG2 mid-rise provisions for concrete buildings. The shearwalls were considered to be unconfined flexural controlled walls will low axial and shear demands. The mullions in the upper stories were assumed to act like rocking elements due to inadequate connections. Thus, their DDL and CDL were set equal to half of the width of the element, or 0.02 in the North-South direction and 0.04 in the East-West direction.

For mid-rise buildings, flexural controlled shearwalls are governed by plastic rotation limits, while VLS components (columns) are governed by drift limits. Both of these limits must be satisfied in order for a structure to be classified as life-safe. For this example the interior columns were assessed as shearwalls due to their large aspect ratio in the East-West direction; their rotation limits were chosen considering their large axial load demand. In their weak direction (North-South), these columns were considered VLS only and were assigned drift limits for VLS columns. The exterior columns at the ground level were designated DDL and CDL limits according to SRG2 recommendations for VLS columns.

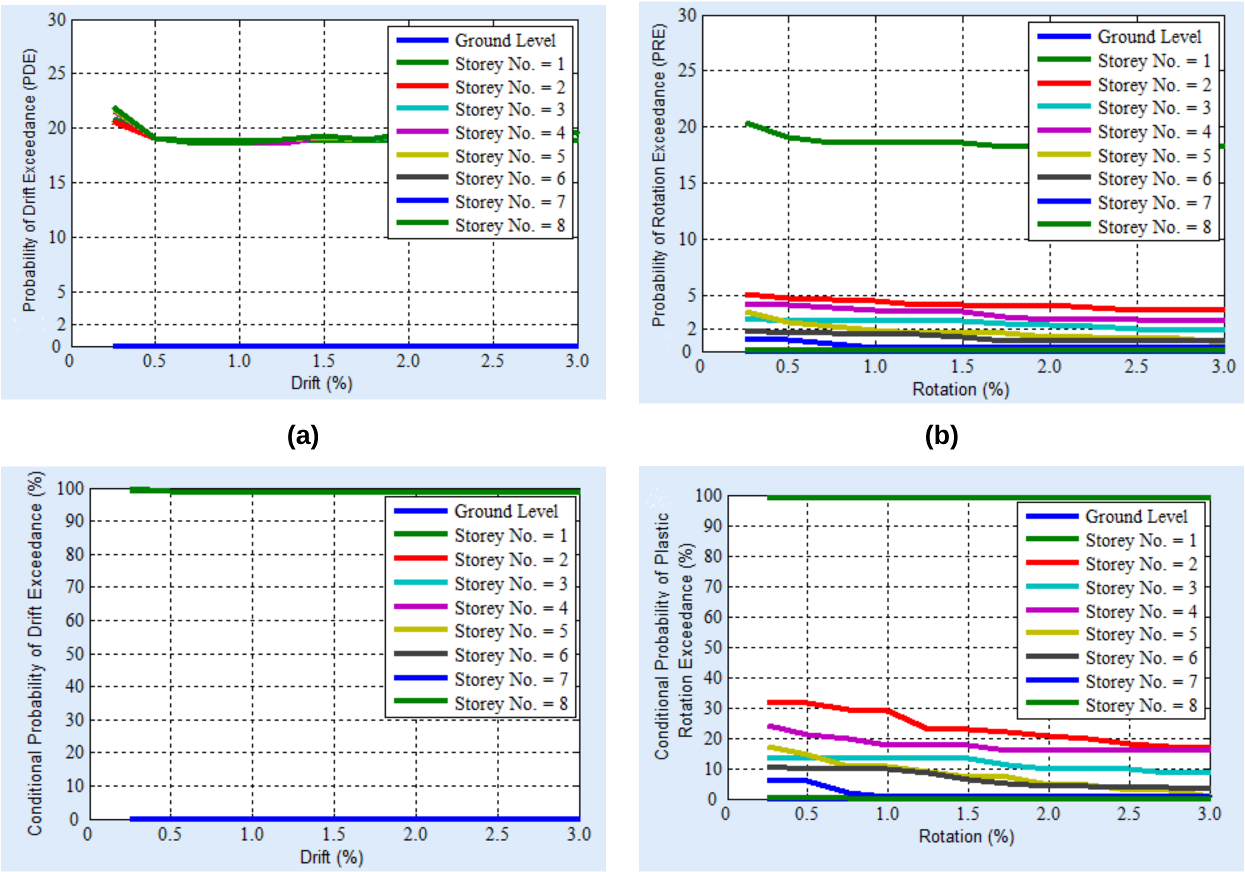
Table 2 – Component Deformation Limits for the Example Building in Each Direction

	North-South Direction		East-West Direction	
	First Storey	Upper Stories	First Storey	Upper Stories
Exterior Columns DDL	**0.007**	-	**0.007**	-
Exterior Columns CDL	**0.008**	-	**0.008**	-
Mullions DDL	-	0.02	-	**0.04**
Mullions CDL		0.02		**0.04**
Interior Columns DRL	-	-	0.003	0.003
Interior Columns CRL	-	-	0.005	0.005
Interior Columns DDL	0.013	**0.013**	-	-
Interior Columns CDL	0.016	**0.016**	-	-
Shearwall DRL	**0.008**	**0.008**	**0.008**	**0.008**
Shearwall CRL	**0.015**	**0.015**	**0.015**	**0.015**

The governing deformation limits for each storey for each direction are bolded and underlined in Table 2. Since the LDRS components are modeled separately, their rotation limits are checked separately. However the VLS components are not modeled, and thus, the DDL and CDL for each storey must be checked for the governing component. The exterior columns govern in the first storey, while the interior columns govern in the upper stories in the North-South direction and the mullions govern in the upper stories in the East-West direction.

4.2. Analysis and Results

The LDRS components described previously were modeled and analyzed in each direction using *Analyzer II*. The PDE and CPDE results for all walls and the PRE and CPRE results for the elevator core walls in the North-South direction are illustrated in Fig. 5. The rotation exceedance results for the other walls are similar and excluded here for brevity. The results are plotted against deformation (drift or plastic rotation) so it is easy to find the governing deformation limits and read the (conditional) probability of exceedance results. For the CPDE and CPRE 5% in 50 year ground motions were considered, as this is the requirement for medium seismic risk. The PDE and PRE are computed over a 50 year period considering all possible levels of shaking.



(a) **(b)**

(c) **(d)**

Fig. 5 – Pre-retrofit Analysis Results in the North-South Direction for: (a) PDE vs. Drift for All Walls; (b) PRE vs. Plastic Rotation for the Elevator Core Wall; (c) CPDE vs. Drift for All Walls; and (d) CPRE vs. Plastic Rotation for the Elevator Core Wall

Because the four exterior shearwalls were discontinuous at the first storey, this storey had very high drift and rotation demands in the North-South direction and did not conform to the criteria in Table 2.The structure did meet the requirements from Table 2 in the East-West direction (not shown here for brevity), but because it has a very high seismic risk in the North-South direction the structure should be retrofit to meet life safety performance.

4.3. Retrofit

Since the North-South direction was critical for this structure, two possible retrofit solutions would be to extend the four discontinuous North-South shearwalls to the ground level, or to add another exterior wall to limit the deformation demands on the existing components. For this example, it is proposed to use a combination of these two solutions. The two Western exterior shear walls are to be extended to the ground and improved to the fourth storey, while a new four storey buttress wall will be added on the South-East side of the building, as illustrated in Fig. 6.

Based on the results of a modal analysis, the non-symmetric example building was suspected to be torsionally sensitive. And since the main walls lie along the centerline of the building, it does not have much torsional resistance. Because of this, a three dimensional (3D) model, that could capture torsional effects, was developed in *Analyzer II* to assess this retrofit scheme. The same governing performance requirements presented in Tables 1 and 2 were considered for the 3D retrofit assessment. Since the retrofit walls would be well confined with low axial loads, they would be capable of deforming to large drifts and plastic rotations and would not govern.

An INDA was performed similar to the 2D case, except that both orthogonal components of the ground motions were applied simultaneously to the 3D model. The resulting deformations in each direction were compared to their respective limits from Table 2. The PDE, CPDE, PRE, and CPRE results are illustrated for the North-South direction in Fig. 7. Once again, only the elevator core walls are shown here for brevity and the CPDE and CPRE were calculated for 5% in 50 year ground motions.

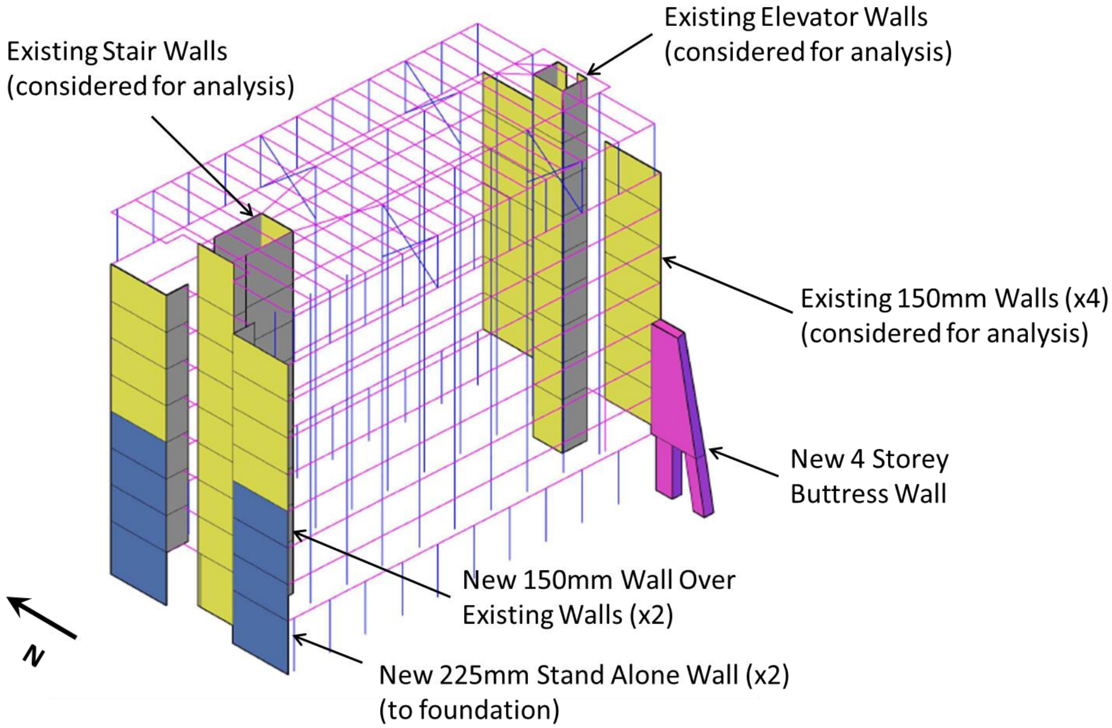
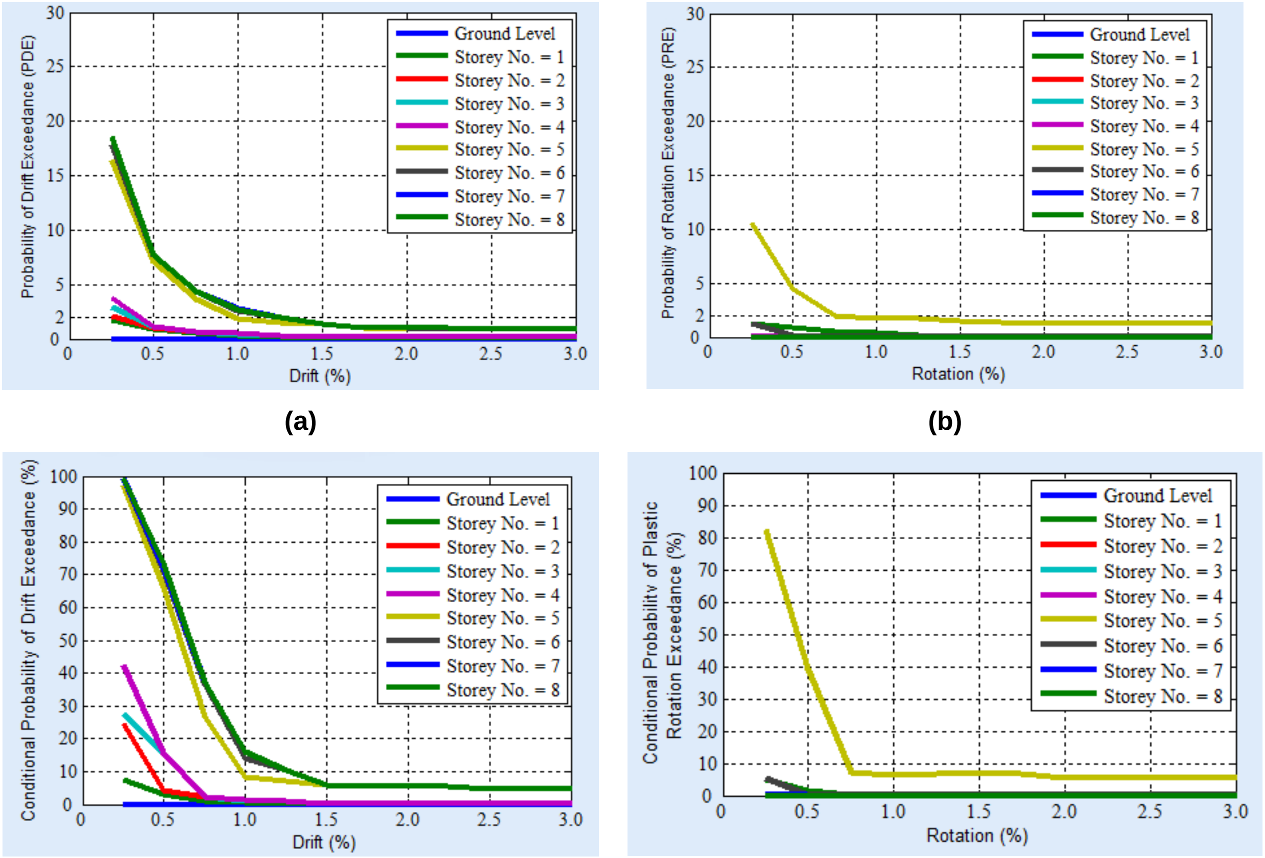


Fig. 6 – Proposed North-South Direction Retrofit

From Fig. 7a it can be seen that the DDL of 0.007 (0.7% drift) in the first storey and 0.013 (1.3% drift) in the upper stories are below 5%, which is acceptable for a medium risk building. Fig. 7b shows a maximum 2% PRE at the shearwall DRL of 0.008 (0.8% rotation). Fig 7c and d show the CDL (0.008, or

0.8% drift, in the first story and 0.016, or 1.6% drift, in the upper stories) and CRL (0.015, or 1.5% rotation, in all stories) are all below the 25% limit. Based on these results, the North-South direction meets the requirements from Tables 1 and 2 for a medium seismic risk structure. The results in the East-West direction are similar to before and still meet the requirements summarized in Tables 1 and 2.

Since both directions now meet the requirements summarized in Tables 1 and 2, this structure can be classified as medium seismic risk, which was the primary goal of the remediation. Also, since this retrofit scheme only requires the addition or improvement of exterior walls, it can easily be done without limiting the functionality of this building during the construction period.



(a) **(b)**

(c) **(d)**

Fig. 7 – Post-retrofit Analysis Results in the North-South Direction for: (a) PDE vs. Drift for All Walls; (b) PRE vs. Plastic Rotation for the Elevator Core Wall; (c) CPDE vs. Drift for All Walls; and (d) CPRE vs. Plastic Rotation for the Elevator Core Wall

5. Conclusion

This paper presented and discussed the methodology implemented for the performance-based seismic analysis of British Columbia mid-rise school buildings. The key components of this methodology are its use of incremental dynamic analysis with sophisticated nonlinear models and the deformation-based performance measures used to quantify risk. The use of INDA is highly time consuming and computationally intensive. Thus, in order to relieve these demands, an online tool called *Analyzer II*, which utilizes HPC methods including cloud and parallel computing, was developed. This allows its users to rapidly and efficiently perform sophisticated probabilistic analyses on online cloud servers, which are accessible from any internet-connected device.

This paper also included a detailed example, which showed how this methodology and tool could be used to assess the seismic risk of a mid-rise structure pre- and post-retrofit. The example comprised a high seismic risk 9 storey concrete shearwall building with a soft first storey. A retrofit was proposed and analyzed using a 3D implementation of the *Analyzer II*. It was shown that by improving the first four stories of the building with the addition of exterior walls the seismic risk of the building could be lowered to a “medium” category without any obstruction to the functionality of the building.

6. Acknowledgements

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