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Multi-Criteria Risk Based Approach for Seismic Evaluation of Existing Buildings in Canada

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ABSTRACT

In this paper, the need for updating seismic evaluation guidelines for existing buildings in Canada is presented. Comparison is made between the basis and rationale of existing seismic evaluation guidelines in Canada and the U.S, namely: 1) the 1993 NRC guidelines, and 2) the American standard (ASCE/SEI 41), as well as the newly proposed risk-based approach under development by the National Research Council Canada. A number of key contributing factors affecting seismic risk of existing buildings due to their failure are explained. A methodology is proposed on how to consider the effect of different contributing parameters.

Keywords: Seismic Evaluation, Existing Buildings, Seismic Risk, Seismic Hazard, Building Code.

INTRODUCTION

The requirements for seismic design of building structures in different building codes have evolved over the last few decades based on the enhanced understanding and knowledge learned from previous major earthquakes, and their consequences on the building structures. The very first provisions for seismic design of new buildings were introduced in the 1941 edition of the National Building Code of Canada (NBC). Therefore, one can suspect that any building constructed prior to the 1941 was not properly designed for earthquake loads, if not designed based on other international building codes. The seismic provisions have become more comprehensive in later editions of the NBC in 1953, 1960, 1965, 1970, 1975, 1977, 1980, 1985, 1990, 1995, 2005, 2010, and 2015 [1].

It is expected that buildings that have been designed as per earlier editions of building codes, in most cases, may not meet the seismic design requirements of the building codes in effect today. Moreover, many earthquakes that occurred across the world during the 20th century have shown the vulnerability of buildings designed as per requirements of previous codes. Lessons learned from previous earthquakes were one of the key factors in the evolution of earthquake engineering and seismic design requirements over the past several decades. Failure of existing buildings during earthquakes can be a concern to life safety objectives, and a large liability for the building owners, as in many cases seismically deficient buildings are ignored. The building owners of such deficient buildings could be surprised by the level of damage their buildings might suffer after a seismic event. Therefore, seismic evaluation of an existing building is necessary to be conducted in order to obtain a better understanding of the expected seismic performance of the existing building, and accordingly to plan for seismic risk mitigation strategies.

SEISMIC EVALUATION OF EXISTING BUILDINGS IN CANADA

Background

The first guidelines for seismic evaluation of existing buildings were developed by the National Research Council Canada (NRC) in 1993 [2]. The 1993 NRC Guidelines were mainly developed based on the *NEHRP Handbook for the Seismic Evaluation of Existing Buildings* (FEMA-178) [3]. The Guidelines considered life-safety objectives without addressing other objectives such as damageability or specific building performance under special conditions. The buildings treated in the Guidelines are ordinary buildings with ordinary occupancies, not unusual or special buildings (e.g. post-disaster buildings), or structures devoted to industrial processes. The recommendations in the Guidelines benefited from a study by Allen [4] on minimum load factors for structural evaluation of existing buildings based on the life-safety goal of the NBC. Allen concluded that the NBC-specified earthquake load can be reduced as a function of the consequences of the potential failure, which are assessed on the basis of redundancy and the likelihood and number of people at risk (life-risk category). Assuming a medium redundancy as recommended by the NRC Guidelines and a normal life-risk category, the risk study determined a reduction factor close to 0.6. However, it was suggested that the evaluator may wish to consider adjusting the 0.6 factor up or down, according to redundancy and life-risk category for each potential failure.

The 1993 NRC guidelines consist of a quick check and a detailed analysis procedure, which identifies the deficiencies in an existing building. The Guidelines recommend that the deficiencies identified in the detailed seismic evaluation to be addressed similar to the guidance of the *NEHRP Handbook of Techniques for Seismic Rehabilitation of Existing Buildings* (FEMA-172) [5]. The American guidelines in the FEMA-178 have gone through several revisions over the years and sequentially evolved to FEMA-310, ASCE/SEI 31-03, and eventually ASCE/SEI 41, with the first edition in 2006 and subsequent revisions in 2013, and most recently in 2017. Therefore, there is a gap and need to bring the NRC guidelines up to speed for seismic evaluation of existing buildings.

Framework for Seismic Risk Management

Public Services and Procurement Canada (PSPC) as the largest public property owner in Canada, reached out to the NRC to provide them with a consistent seismic risk management tool for assessing their large portfolio of existing buildings, which led to the development of a comprehensive seismic risk management framework for the existing buildings in the portfolio of PSPC buildings [6]. Figure 1 presents a sieving analogy for seismic risk assessment of a large portfolio of existing buildings owned or managed by PSPC. It was suggested to develop a seismic screening procedure, which consists of Level 1 - Preliminary Seismic Risk Screening Tool (PST), and a Level 2 - Semi-Quantitative Seismic Risk Screening Tool (SQST) for structural and nonstructural components to prioritize the inventory of existing buildings, as well as to identify the existing buildings that can be exempted from further seismic risk assessment, depending on their level of seismicity, consequence of failure, or the edition of the building code they were originally designed according to. The development of the Level 1 – PST and Level 2 - SQST have been completed by the NRC [7], [8]. The third level (Level 3) in the seismic risk management framework is to modernize the seismic evaluation guidelines of NRC that were initially developed in 1993. In the proposed seismic evaluation guidelines, the seismic evaluation starts with a Quick Evaluation procedure, which can lead to a Deficiency-Based Evaluation. After performing the Deficiency-Based Evaluation, a Detailed Evaluation may be required to reach the final decision which varies from: 1) No Action, 2) Major Retrofit, 3) Immediate Action or Demolition/Disposal.

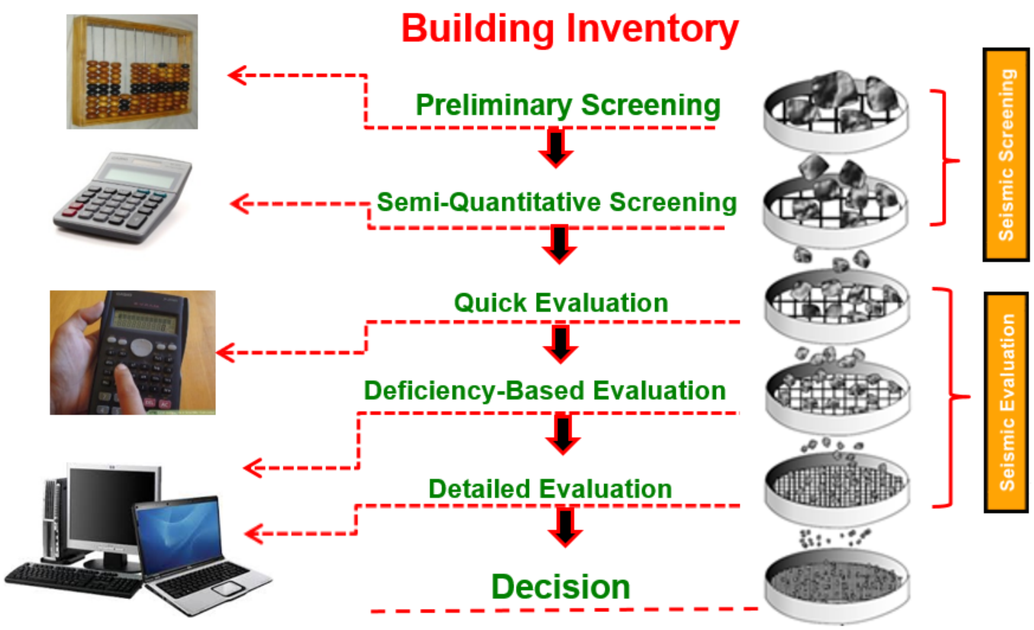

Figure 1. Components of framework for seismic risk management.

In the following sections, the differences between the ASCE and the NRC requirements for seismic evaluation of existing buildings and the cross-border differences in seismic design philosophies are discussed. Then the rationale for the new multi-criteria risk-based approach for seismic evaluation of existing buildings is presented.

ASCE/SEI 41-17

The American standard for seismic evaluation and retrofit of existing buildings (ASCE/SEI 41-17) adopted a performance-based seismic design approach in its provisions and requirements [9]. The performance-based design approach in ASCE/SEI 41 prescribes the design/evaluation of a building for a specific performance objective. Performance objectives include specific performance levels for given hazard levels. In ASCE/SEI 41-17 building performance levels are defined as a combination of structural performance levels and nonstructural performance levels, ranging from 1-A, to 6-D [9]. Structural performance levels include: immediate occupancy (S-1), damage control (S-2), life safety (S-3), limited safety (S-4), collapse prevention (S-5), and not considered (S-6). Nonstructural performance levels include: operational (N-A), position retention (N-B), life safety (N-C), hazard reduced (N-D), and not considered (N-E).

ASCE/SEI 41-17 recommends existing buildings to be evaluated for two levels of seismic hazards according to their risk categories (which are similar to importance category in the NBC) and building performance levels. For instance, risk category I, and II buildings, which are similar to low and normal importance buildings in Canada are to be evaluated for Life Safety Performance Level (3-C) for hazard levels that have 20% chance of exceedance in 50 years, and Collapse Prevention Performance Level (5-D) for hazard levels that have 5% chance of exceedance in 50 years [9]. In addition, ASCE/SEI 41-17 provides different global and local limiting parameters for different Seismic Force Resisting Systems (SFRS) made of steel, concrete, masonry or wood. These criteria are set to ensure that a certain performance level is met for a specific level of strong ground motion. These global and local parameters include drift ratios, and plastic rotation angles for beams, columns, and walls [9].

Unlike the 1993 NRC Guidelines in which the quick check and detailed analysis procedures are sequential, in the ASCE/SEI 41-17, seismic evaluation of existing buildings is to be performed in three Tiers, namely: Tier 1 Screening Procedure, Tier 2 Deficiency-Based Evaluation Procedure, and Tier 3 Systematic Evaluation Procedure. Only those buildings that comply with prescribed height restriction (depending on type of SFRS, level of seismicity, and building performance level) are permitted to be evaluated using Tier 1, and Tier 2. The height restrictions have evolved in ASCE/SEI 41 based on lessons learned from previous major earthquakes. Similar to the ASCE/SEI 41-17, the NRC is in the process of developing a new multi-tier seismic evaluation guideline, while considering life safety objective using a risk-based approach.

Risk-Based Approach for Seismic Evaluation

A risk-based approach for seismic evaluation of existing buildings should consider all key parameters contributing to the seismic risk. By definition, the seismic risk of buildings is the probability of failures of buildings times the consequence of failure. Therefore, for a given acceptable seismic risk level, when the consequence of failure is higher, a lower probability of failure is required. The probability of failure of an existing building on a given location depends on the site-specific seismic hazard, building characteristics, including: SFRS type, redundancy degree in the SFRS, quality of inspection, state of damage and deterioration, and the remaining occupancy time of the building. In the following sections, the seismic hazards and the consequences of failure will be discussed in detail.

Seismic Hazards

In the NBC 2015, site-specific seismic hazard values corresponding to a chance of exceedance of 2% in 50 years is selected for seismic design of new buildings, similar to its 2010 and 2005 editions. The main difference in the NBC 2015 compared to its previous editions is that it determines seismic hazard values based on the mean values of spectral response accelerations rather than median values used in NBC 2010 and NBC 2005.

The risk-targeted maximum considered earthquake (MCE_R) was introduced in the 2010 edition of ASCE/SEI 7 and was adopted in ASCE/SEI 41-13 and ASCE/SEI 41-17 [9]. The MCE_R is defined as the spectral response accelerations in the direction of maximum horizontal response represented by a 5% damped acceleration response spectrum that is expected to achieve a 1% probability of collapse within a 50-year period. The risk coefficients, namely the ratios of MCE_R ground motions to ground motions with probability of exceedance of 2% in 50 years, are within the range between 0.9 and 1.0 for the majority of locations across the United States [10].

Allen et al. [11] investigated the applicability of risk-targeted ground motions for future editions of the NBC. The risk coefficients (i.e., the proposed adjustment factors from 2% in 50-year mean seismic hazards) presented in the study is dependent on the level of acceptable risk or collapse risk objective. Allen et al. indicated that moderate variability exists in the risk coefficient across Canadian localities, with all localities showing a slight reduction in design ground motions relative to the proposed 2% in 50-year hazard values in NBC 2015 (with the largest potential observed changes in design ground motions on the west coast of Vancouver Island, with risk coefficients of around 0.85, suggesting structures in these localities being overdesigned by 15%). Given the preceding discussion, the design earthquake in the NBC 2015 is deemed comparable with the MCE_R in ASCE /SEI 41-17.

Assuming that earthquake loads, and buildings resistance against these loads are independent normal variables, a relationship between the reliability index, probability of failure in 50 years, and the earthquake load reduction factor can be obtained. Table 1 presents the variation of probability of failures and corresponding seismic load factors for different reliability index values (0.25 increments of reductions in reliability index). The seismic load reduction factor is normalized for new buildings to be 1.0, i.e. 100% of the requirements for new buildings. As expected the lower the reliability index is, the higher will be the probability of failure, and the lower will be the seismic load factor. In seismic evaluation, this corresponds to the fact that, if an existing building, for instance, complies with 50% of the load requirements of the new buildings, the probability of its failure is six (6) times higher than that of a new building.

Table 1. Reliability Index, Probability of Failure, and Seismic Load Factors.

	Reliability Index	**Probability of Failure in 50 Years**	**Seismic Load Factor**
New Seismic Design	2.30	1.0 %	1.00
Reduced Reliability for Seismic Evaluation of Existing Buildings	2.05	2.0 %	0.80
	1.80	3.6 %	0.63
	1.55	6.0 %	0.50
	1.30	9.6 %	0.40
	1.05	14.8 %	0.33

Consequences of Failure

The failure of buildings can pose different levels of consequences associated with seismic risk to life safety. The NBC 2015 addresses different levels of consequence of disruption in use of buildings due to seismic induced failure of new buildings by considering low, normal, high, and post-disaster importance categories. The increase in importance results in an increase in buildings' capacity and in turn reduces the probability of failure given the design level of earthquake shaking. However, the importance categories do not consider other applicable key factors contributing to the consequences of failure such as the number of storeys, size of buildings, and number of occupants. For example, although a one-storey office building and a twenty-storey office building are classified as normal importance category, the consequence of failure of these two buildings is significantly different due to the fact that the taller office building can accommodate significantly more occupants than the one-story building does. To address this, a consequence classification consisting of Low (CC-L), Medium (CC-M), and High (CC-H) consequence classes, was proposed by Fathi-Fazl and Lounis [12]. A graphical illustration of consequence classes is shown in Figure 2 for a spectrum of consequences of failure from very low consequence to very high consequence. Ten typical types of building occupancy were considered including: office, public, commercial, residential, industrial, educational, care/treatment, parking, public assembly, and passenger stations occupancies have been defined as functions of the total floor area and the number of storeys in the building [12]. In general, the larger a building is both in total area, and number of storeys, the higher its consequence of failure will be. This is due to the fact that larger buildings shelter a higher number of people and failure of such buildings can potentially pose threats to more human lives.

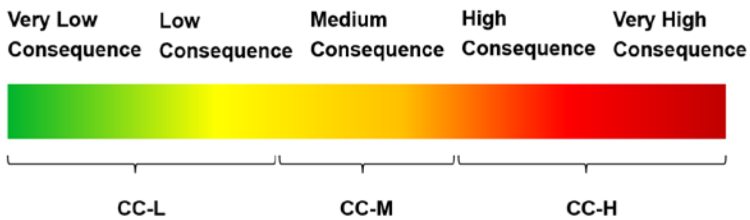

Figure 2: Seismic Consequence Classes of Failure

In the proposed seismic evaluation procedures being developed by the NRC, the consequence of failure is considered by adjusting the acceptable reliability index, and consequently the probability of failure. As shown in Table 1, different load factors can be suggested depending on the level of reduced reliability for seismic evaluation of existing buildings and acceptable probability of failure. For parameters such as inspection quality and state of damage and deterioration that are qualitative in nature, adjustment in acceptable reliability index can be suggested to account for these qualitative parameters. However, for the remaining occupancy time of an existing building, seismic load factors can be calculated quantitatively. These load factors correspond to the acceptable probability of failure over the remaining occupancy time of an existing building instead of 50 years that are considered for a new building.

CONCLUSIONS

A multi-criteria risk-based approach for seismic evaluation of existing building is presented to assist the stake holders and building owners in making risk-informed decisions, on whether to take action to retrofit an existing building or not. The proposed multi-tier seismic evaluation guidelines will provide Quick Evaluation, Deficiency-Based Evaluation and Detailed Evaluation procedures that can be used, depending on the total height of the SFRS. It has been discussed that beside the level of seismic hazard, there are other key parameters contributing to the seismic probability of failure, such as type of SFRS and construction material, redundancy in the SFRS, quality of inspection, state of damage and deterioration, and the remaining occupancy time of the building. Furthermore, when assessing the seismic risk in existing buildings, not only the probability of failure is important, but also the consequence of failure should be factored in.

The methodology presented herein aims to account for different parameters contributing to the seismic risk by assessing their effect on the reduced acceptable reliability index for seismic evaluation of existing buildings. This will lead to different seismic load factors which can be used for the seismic evaluation of existing buildings.

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