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THE ADAPTATION OF THE FEMA 154 METHODOLOGY FOR THE RAPID VISUAL SCREENING OF EXISTING BUILDINGS IN ACCORDANCE WITH NBCC-2005

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ABSTRACT

The detection of probable losses caused by an earthquake, one of the destructive phenomena of nature, can reduce the risk of serious injury or loss of life in a region. Score assignment methods can be applied in a multiphase seismic risk evaluation approach for a group of buildings to detect the structures for detailed analysis, based on their seismic vulnerability. Considering the fact that the existing Canadian rapid visual screening procedure has not been updated since 1992, a set of structural vulnerability indices and modifiers are calculated in this paper, using the national-wide spectral acceleration response values of the NBCC-2005 for the three seismicity regions (low, moderate and high) in Canada. The proposed SIVs and modifiers for the building height, irregularities, and design and construction year are calculated for the NBCC-2005 site soil class C. The modifiers for soil condition adapt the SIV for other soil classes. The assessment results of a comprehensive seismic vulnerability evaluation project done through the proposed method and the current Canadian procedure are compared at the end.

Introduction

Estimating the probable future losses is of great importance to those in charge of public safety or management of facilities in earthquake-prone regions. Different types of loss estimation studies may be used depending on the nature of the problem at hand and the purpose of the study (Coburn & Spence 2002). The assessment of the seismic vulnerability is a key element in every loss estimation study. There are two principle methods used for this mean, one based on *predicted vulnerability* and the other using the *observed vulnerability* (Sandi 1982).

The *observed* vulnerability assessment is based on statistics of past earthquake damages, that can be completed by the experts' opinion to provide damage probability matrices; DPMs, which describe the probability that a building class is in a specific damage state for a given level of hazard. This method is also suitable for non-engineered structures constructed using low-strength materials for which earthquake resistance is difficult to calculate but with substantial statistical damage data. The *predicted* vulnerability evaluation on the other hand, can be applied to assess the seismic vulnerability of buildings when sufficient observed data is not available. This method refers to the evaluation of the expected performance of building classes based on calculations and design specifications and it can be done by simple analytical models or detailed analysis procedures depending on the objective of the assessment. Analytical models can also be applied to define the capacity curves of typical buildings, representing a

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given building class, which are then combined with the seismic demand to produce the vulnerability curves for each of the building classes according to the damage states definition. This procedure can be used to develop scores, which correlate potential structural deficiencies with structural characteristics for different building classes. This is the basis of a seismic vulnerability assessment method called score assignment.

Score Assignment Method

The score assignment method in Canada was initiated by the publication of the *Manual for Screening of Buildings for Seismic Investigation* (NRC-IRC 1992). A set of structural (SI) and non-structural (NSI) indices are presented for 15 building types and a screening procedure is established to calculate a seismic priority index (SPI) for each building as the sum of the structural and non-structural indices as shown in Equation (1). Buildings are ranked according to their scores and divided into 4 categories. An SPI higher than 20 indicates that the building is in the high priority category and requires a detailed analysis while a structure with an SPI above 30 is considered to be in a critical condition. Structures with SPI between 10 and 20 and lower than 10 are considered to have moderate and low priorities, respectively.

$$SPI = SI + NSI \tag{1}$$

This methodology is based on a procedure, initiated in the United States in 1988 with the publication of the FEMA-154 (ATC 2002a) and its companion, FEMA 155 (ATC 2002b), which were updated in 2002. The methodology in the updated manuals is founded on the simplified inelastic analysis procedure of ATC 40 (ATC 1996), a version of the capacity-spectrum method that is based on the equivalent linearization. For each seismicity region and each building class, a Basic Structural Hazard score (BSH) is computed. Those BSH are related to the probability of collapse of the building class given a specify level of seismic hazard. Score modifiers are applied to the BSH for the structures that may have different characteristics and deficiencies from those assumed in the calculation of the initial BSH scores. The buildings with final scores lower than 2 should be analysed in further detail.

Unlike FEMA 154 methodology, the structural indices in the Canadian manual do not have any probabilistic interpretation and are mainly developed by considering the different concepts for base-shear force calculation in different versions of the National Building Code of Canada (NBCC); It compares the degree of conformity of the assessed structures to the NBCC 1990. In view of the recent modifications proposed in the new NBCC 2005, especially concerning the regional seismicity, the soil classification and the calculation of the base-shear force, its application must be considered with care.

Recent studies (ATC 2005, Powell 2006) indicate that the capacity spectrum method (ATC 40) applied to calculate the scores in FEMA-154, leads to very large overestimations of the maximum displacement for relatively short-period systems with periods smaller than about 0.5s. Approximate maximum displacements in this period range can be, on average, larger than twice the real displacements. It is also shown that the procedure generally underestimates the maximum displacement of the systems with higher periods by a value of 30% of the real displacement.

The main objective of this paper is to develop necessary tools for a score assignment method for different regions of seismicity in Canada. This is done by the application of (1) the national-wide spectral acceleration response values and the spectral amplification factors presented in the recent National Building Code of Canada (2005), (2) the capacity and the fragility curves for different building classes (NIBS 2003), and (3) the improved nonlinear static analysis procedure of FEMA 440 (ATC 2005).

Development of Indices

Structures classification and seismicity

FEMA 154 uses the short- and one-second- period spectral acceleration response values of the three seismicity regions in United States as the seismic demands in its approach to calculate the BSH and score modifiers. With the development of the new seismic hazard model for Canada (SEE CJSE 2003), using the national-wide spectral acceleration response values of the NBCC (2005) as seismic inputs for the computation of a set of structural vulnerability indices and index modifiers can be done more easily. In this way, the developed indices are associated with damage probability interpretations besides their ability to rank buildings for further investigations.

The calculation of the structural vulnerability indices (SVI) are based on the improved nonlinear static analysis procedure of FEMA 440. It should be mention that the modification of capacity and fragility curves for the building classes with the construction reality in Canada is not presented in this paper but is now under investigation. The building classification used in this paper is the one presented in the current rapid visual screening methodology in Canada (Table 1) which is in fact, similar to the classification of FEMA 154.

Table 1. The building classification used in the development of the indices (IRC-NRCC 1992).

Building Class Sign	Structural Description	FEMA 154 Classes
WLF	Light wood frame	W1
WPB	Wood post and beam	W2
SMF	Steel Moment resisting frame	S1
SBF	Steel braced frame	S2
SLF	Steel light frame	S3
SCW	Steel frame with concrete shear wall	S4
SIW	Steel frame with infill masonry wall	S5
CMF	Concrete moment resisting frame	C1
CSW	Concrete shear wall	C2
CIW	Concrete frame with unreinforced masonry infill	C3
PCW	Prefabricated concrete wall	PC1
PCF	Prefabricated concrete frame	PC2
RML	Reinforced masonry bearing walls with wood or metal diaphragms	RM1
RMC	Reinforced masonry bearing walls with concrete diaphragms	RM2
URM	Unreinforced masonry bearing walls	URM

The Spectral acceleration response values of 640 cities in Canada are presented in NBCC 2005. Based on the FEMA 310 criteria (Table 2), these 640 cities were divided into 3 groups according to their respective seismicities. Similar to the methodology of FEMA 154, three sets of Structural Vulnerability indices and index modifiers are calculated for the three regions of seismicity in the country (low, moderate and high).

Table 2. The Criteria to Specify the Seismicity of Cities in Canada (ASCE. 1998).

Region of Seismicity	Sa(0.2)	Sa(1.0)
High	> 0.500g	> 0.200g
Moderate	0.167g to 0.500g	0.067g to 0.200g
Low	< 0.167g	< 0.067g

For typical seismic hazard computations in Canada, the mean hazard value lies between the 65th and 75th percentiles of the hazard distribution (Adams & Atkinson 2003). To avoid any underestimation caused by the epistemic uncertainty which arise from the incomplete knowledge of the physical mechanisms, the median plus one standard deviation values of the spectral accelerations (84th percentile) are considered here as the hazard level in the development of the indices.

To exclude the repetition of the data for adjoining cities with similar spectral values, the data of those cities were considered only once in the statistical calculation. The median plus one standard deviation of the spectral acceleration values for each seismicity region (Table 3) was then used in the calculation of the SVIs for different building classes.

Table 3. Spectral Acceleration Values Used in the Calculation of the Indices.

	High Seismicity	**Moderate Seismicity**	**Low Seismicity**
$S_a(0.2)$	1.31	0.55	0.14
$S_a(0.5)$	1.31	0.55	0.14
$S_a(1.0)$	0.81	0.28	0.08
$S_a(2.0)$	0.43	0.13	0.04

Development of the structural vulnerability index SVI

The structural vulnerability indices are defined as the negative of the logarithm (base 10) of the probability of collapse given the seismic demand corresponding to the considered seismic hazard level for each region (Equation (2)).

$$SVI = -\text{Log}_{10}[P(\text{collapse} \mid \text{seismic demand})] \quad (2)$$

This approach is based on the development of the basic structural hazard of FEMA-154 and requires the use of fragility functions produced from past earthquake damage observation data and/or analytical models, such as shown on Figure 1.

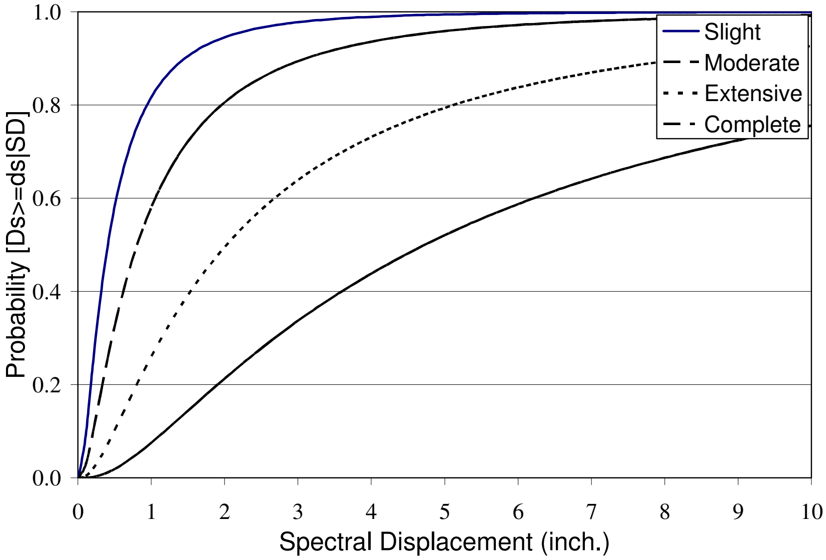


Figure 1. Example of Fragility Curves for URM Buildings Designed to a Moderate-Code Seismic Design Level (NIBS 2003).

The complete damage state curves are used to obtain the probability of complete damage for the spectral displacement corresponding to the performance point of the structure. This performance point is obtained from the capacity spectrum method and represents the condition for which the seismic capacity of the structure is equal to the seismic demand imposed on the structure by a specific ground motion (ATC 1996). The seismic demand was defined according to the three seismicity regions defined in Table 3.

The FEMA 440 improved nonlinear static analysis procedure (ATC 2005) is used in the equivalent linearization method for modeling the nonlinear response of a building as a SDOF system. The maximum displacement of the nonlinear system is estimated with an equivalent linear system using an effective period, T_{eff}, and effective damping, β_{eff} . In the application of this procedure, we start by plotting the capacity curves and the seismic demand spectra in the acceleration-displacement response spectrum (ADRS) format. The maximum displacement of each building group representation is then determined from a point on the capacity spectrum that lies on the appropriate demand response spectrum, reduced for the nonlinear effects. The reduction factor in FEMA 440 is given as Equation (3).

$$B = \frac{4}{5.6 - \ln \beta_{eff} (\%)} \tag{3}$$

The effective damping in this equation consists of the hysteretic damping and the elastic damping (β_0) for each building class. FEMA 440 presents different equations for the calculation of the hysteretic damping based on the inelastic behaviour and the ductility of the structure. Equations independent of the hysteretic model of the structure were used and have been optimized for application in any capacity curve for a wide range of ductilities. The elastic damping values on the other hand, are selected according to the building type, reflecting the inherent differences in the damping behaviour of different materials. The resulting Structural Vulnerability Indices developed for low, moderate and high seismicity regions are listed in Table 4.

Table 4. Structural Vulnerability Indices for Different Seismicity Regions in Canada.

Seismicity	**WLF**	**WPB**	**SMF**	**SBF**	**SLF**	**SCW**	**SIW**	**CMF**
High	3.0	3.5	2.3	2.6	2.5	2.4	1.8	2.0
Moderate	4.8	5.0	3.7	3.8	3.7	3.7	3.6	3.3
Low	7.2	7.3	5.7	5.9	5.8	5.9	5.8	5.4
	CSW	**CIW**	**PCW**	**PCF**	**RML**	**RMC**	**URM**	
High	2.4	1.5	1.9	2.2	2.4	2.4	1.5	
Moderate	3.7	3.3	3.5	3.4	3.8	3.9	2.8	
Low	6.2	5.5	4.9	5.8	5.9	6.0	3.7	

Development of index modifiers

The Structural Vulnerability Indices shown in Table 4 have been calculated for the low-rise building class on soil type C (360–750 m/s average shear wave velocity in the uppermost 30 m) in each seismicity region. However, the procedure should be able to screen other buildings, which may have different characteristics from those assumed in the calculation of the SVIs. For this reason, and as in the FEMA 154 methodology, a variety of index modifiers need to be developed in order to take into consideration, other probable conditions that may exist for the building classes such as:

(i) Different soil class: Classes D and E of NBCC 2005 (modifiers are not proposed for sites with soil classes A or B, thus not to benefit form the better soil condition).
(ii) Horizontal and vertical irregularities
(iii) Design and construction year: pre-code and post-benchmark.
(iv) Different building height: mid-rise and high-rise.

The approach toward calculating these modifiers are mainly similar to the one applied in the computation of the score modifiers in FEMA 154. It should be mentioned that the soil modifiers are computed by re-calculating the SVI after application of the appropriate spectral amplification factors to the demand response spectrum, as presented in the NBCC 2005. Examples of these modifiers are shown in Tables 5 and 6.

Table 5. Index Modifiers for Soil Classes.

Seismicity	Soil Class	WLF	WPB	SMF	SBF	SLF	SCW	SIW	CMF
High	D	-0.1	-0.2	-0.1	-0.2	-0.1	-0.1	-0.1	-0.1
	E	-0.6	-0.9	-0.6	-0.7	-0.6	-0.7	-0.4	-0.6
Moderate	D	-0.5	-0.6	-0.6	-0.5	-0.4	-0.6	-0.6	-0.5
	E	-1.3	-1.3	-1.3	-1.1	-1.1	-1.2	-1.3	-1.2
Low	D	-0.6	-0.6	-0.7	-0.6	-0.6	-0.6	-0.6	-0.7
	E	-1.5	-1.5	-1.5	-1.4	-1.4	-1.6	-1.5	-1.7
		CSW	**CIW**	**PCW**	**PCF**	**RML**	**RMC**	**URM**	
High	D	-0.2	-0.1	-0.1	-0.2	-0.2	-0.2	-0.1	
	E	-0.8	-0.4	-0.5	-0.7	-0.7	-0.7	-0.4	
Moderate	D	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6	-0.4	
	E	-1.4	-1.3	-1.3	-1.3	-1.4	-1.4	-0.8	
Low	D	-0.6	-0.6	-0.5	-0.6	-0.6	-0.6	-0.3	
	E	-1.7	-1.5	-1.2	-1.6	-1.5	-1.5	-0.8	

Table 6. Index Modifiers for Building Height.

Seismicity	Height	WLF	WPB	SMF	SBF	SLF	SCW	SIW	CMF
High	Mid-Rise	NA	NA	0.4	0.3	NA	0.4	0.4	0.3
	High-Rise	NA	NA	0.4	0.6	NA	0.7	0.6	0.4
Moderate	Mid-Rise	NA	NA	0.0	0.2	NA	0.4	0.2	0.2
	High-Rise	NA	NA	0.1	0.4	NA	0.4	0.2	0.2
Low	Mid-Rise	NA	NA	-0.5	-0.4	NA	-0.3	-0.5	-0.3
	High-Rise	NA	NA	-0.5	-0.1	NA	-0.4	-0.6	-0.7
		CSW	**CIW**	**PCW**	**PCF**	**RML**	**RMC**	**URM**	
High	Mid-Rise	0.3	0.2	NA	0.3	0.3	0.3	0.1	
	High-Rise	0.6	0.3	NA	0.3	NA	0.5	NA	
Moderate	Mid-Rise	0.2	0.0	NA	0.1	0.1	0.0	0.5	
	High-Rise	0.4	-0.1	NA	0.1	NA	0.1	NA	
Low	Mid-Rise	-0.5	-0.4	NA	-0.6	-0.1	-0.3	1.8	
	High-Rise	-0.6	-0.7	NA	-0.7	NA	-0.4	NA	

*NA: Not Applicable

Criteria for a detailed analysis

In general, a cut-off index is defined for score assignment procedures to identify buildings requiring a detailed analysis. According to Equation (2), the structural vulnerability index is proportional to the collapse probability of a building given a specific level of seismic hazard. Based on the SVIs calculated for different building classes in Table 4, the approximate number of buildings expected to collapse is computed for a city within the high-seismicity region of Canada, assuming that no index modifier is applicable. The total number of buildings is assumed to be 20000, with a building type distribution similar to the one in downtown Victoria in British Columbia, where the distribution of the wood, unreinforced masonry and concrete moment resisting frame buildings are 65%, 28% and 7%, respectively (Onur 2001).

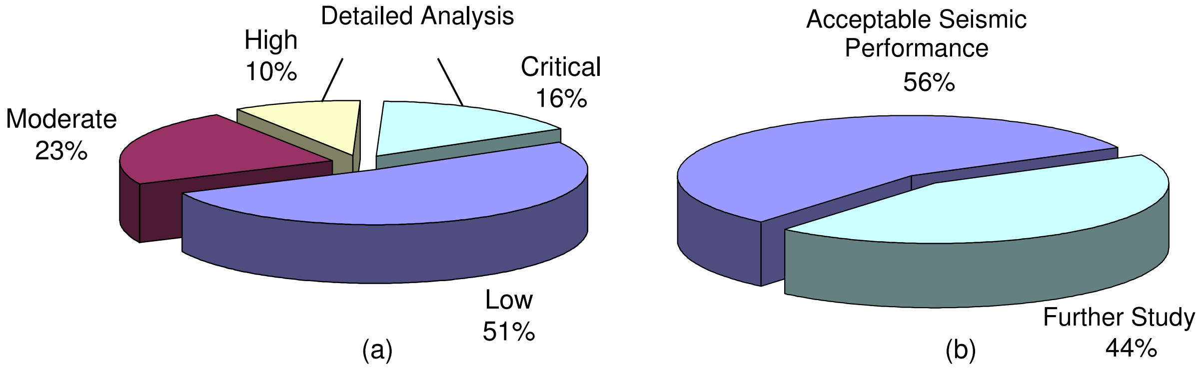
It is observed that the total number of the buildings to collapse is 204 (Table 7), which represents an index of 1.99 in this case (Equation (2)). According to this example and because of the concentration of the potential life loss in URM structures, the jurisdiction may decide that a cut-off score between 1.5 and 2 is appropriate. Ideally, each community should give some thought to the costs and benefits associated with seismic safety, and then decide what cut-off index is appropriate for their particular situation. Based on such explanation, for Canada, a cut-off index equal to “2” can be considered acceptable for all building classes at this time.

Table 7. Evaluation of the Cut-Off Index.

Type	No. of Buildings	SVI	Prob. of Collapse	Expected No. of Bldgs. to Collapse
URM	5600	1.5	0.0316	177
CMF	1400	2.0	0.01	14
WLF	13000	3.0	0.001	13

Comparison of the Scoring Systems

Both the current rapid visual screening procedure in Canada (IRC-CNRC 1992) and the proposed RVS method in this paper offer the possibility of ranking the buildings according to structural seismic vulnerabilities; however, only the proposed RVS method can lead to the determination of the damage probability distribution for building groups in a region. Based on a recent comprehensive study done for a group of buildings in Québec City, the results of building ranking from both methods are compared in Figure 2. As all the buildings are located in the same city, the seismicity level does not influence the ranking. The local site conditions were carefully determined from the geotechnical data (LeBoeuf and Nollet, 2006) and the site soil class was assigned to each building according to the NBCC 1990 and the new NBCC 2005 soil classifications for the IRC-CNRC 92 procedure and the proposed RVS method, respectively.



(a) (b)

Figure 2. Division of the Building Inventory in Quebec City according to the priority for further study: (a) IRC-CNRC 1992 (b) Developed RVS method.

Considering the Seismic Priority Index of the IRC-CNRC procedure and the Final Score of the developed RVS method, both methods give a similar percentage for the structures being in the safe margin. If the “final score below 2” from the proposed method in this paper is considered equivalent to the “critical and high condition" categories of IRC-CNRC 92, it can be seen that the developed procedure is more conservative in determining the buildings which need to be studied in detail (44% versus 26%). This can be explained according to different facts:

- (i) The SPI of the IRC procedure indicates if the structure is in conformity with the seismic provision of the 1990 NBCC, while the final score of the developed RVS method is an indication of the probability of collapse.
- (ii) In the developed RVS method, the index modifiers for vertical irregularity have been calculated based on the assumption that if they were the only modifiers to be considered in the evaluation process, the final index would be less than the cut-off edge.
- (iii) It has been observed that the consideration of the site effect (soil class) is more significant on the indices calculated through the developed RVS method than those obtained from the IRC procedure.

Unlike the IRC procedure, the proposed RVS method does not take into account the non-structural elements in the calculation of the final building indices. Therefore, for a better comparison, the distribution of the "structural indices" for the building inventory in Quebec City is shown in Figure 3 along with the final score from the developed RVS method. In this case if a structural index (SI) greater than 10 is considered as an indication that a detailed analysis is required, then 35%.of the building inventory show up to need further study. This is closer to the result from the developed RVS method (44%) in comparison with the case observed in Figure 2, which indicates that disregarding the effect of the non-structural elements causes the results from the two methods to be more similar.

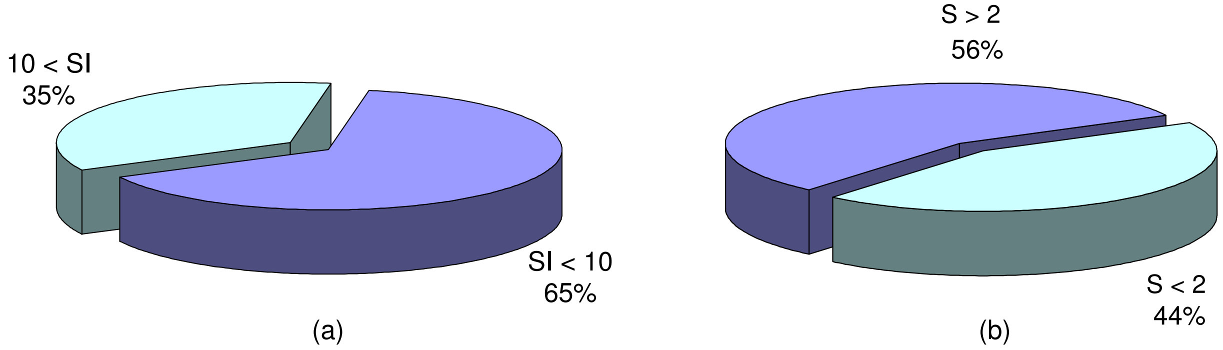


Figure 3. Division of the Building Inventory in Quebec City according to the structural indices: (a) IRC-CNRC 1992 (b) Developed RVS method.

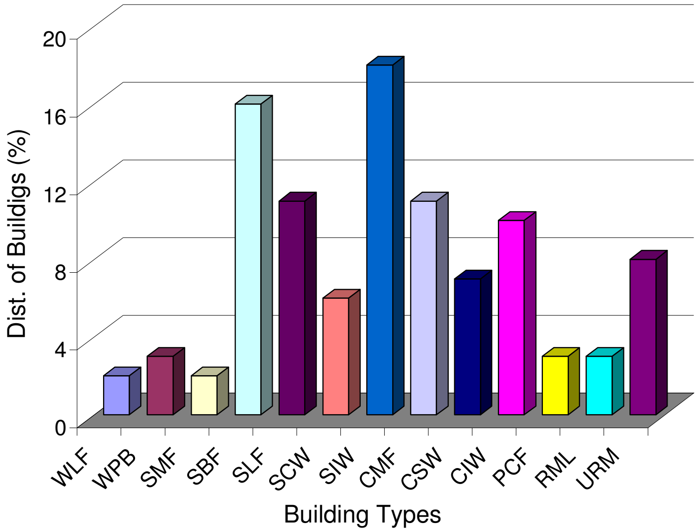
Only the proposed RVS method can lead to the determination of the damage probability distribution for building groups. The distribution of such probability for the building classes in the Quebec City project is shown in Figure 4. It should be noted that Figure 4(b) shows the contribution of the different building types in a damage scenario given the seismic demand considered (moderate seismicity in this case).

Conclusions

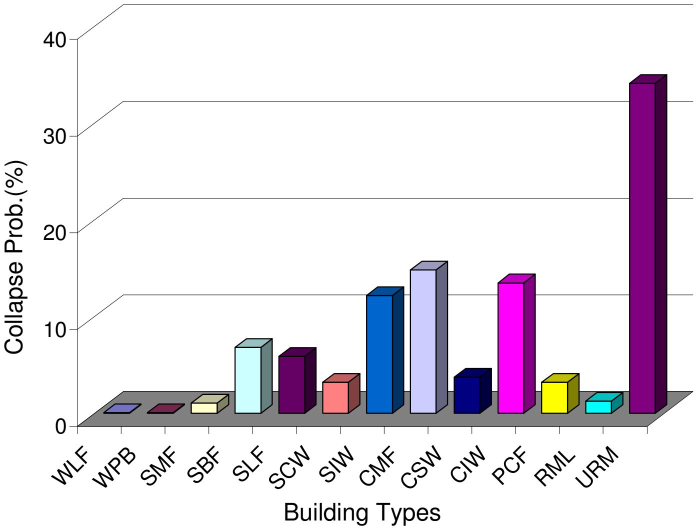
The recent changes in the NBCC 2005 raised the concern on the applicability of the existing Canadian rapid visual screening procedure (IRC-CNRC, 1992). A scoring method for evaluating the seismic vulnerability of existing building considering the new spectral acceleration given in the NBCC 2005 is proposed. The Structural Vulnerability Indices and the index modifiers were computed based on the FEMA 154 rapid visual screening procedure including the improved nonlinear static analysis procedure of FEMA 440 (ATC 2005).

As mentioned in the previous sections, the current Canadian assessment procedure determines the critically condition buildings according to the seismic provisions of National Building Code of Canada 1990. This leads to the underestimation of the seismic vulnerability assessment of any building constructed according to the recent codes (NBCC95 and NBCC 2005) but on poor soil conditions. The proposed RVS method deals in a better way with this condition as it considers the soil modifiers according to the NBCC 2005.

The method considered in this paper to calculate the vertical irregularity modifiers might unnecessarily penalize the structures with high SVIs, by causing them to fall below the cut-off index and therefore, systematically neglecting the influence of the year of conception. A more refined classification of the existing irregularities in buildings can help to better examine their influence on the results of the seismic vulnerability scoring method.



(a)



(b)

Figure 4. Estimating the Collapse Probability for a Building Inventory in Quebec City: (a) building types distribution (%), and (b) collapse probability distribution among the existing building classes in a damage scenario.

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Reference

Adams, J. and G. Atkinson, 2003. Development of seismic hazard maps for the proposed 2005 edition of the National Building Code of Canada, *Canadian. Journal of Civil Engineering* 30(2), 255-271.

ASCE, 1998. *Handbook for the Seismic Evaluation of Buildings - A Pre-standard (FEMA 310)*, American Society of Civil Engineers, Washington D.C.

ATC, 1996. *Seismic Evaluation and Retrofit of Concrete Buildings (ATC 40)*, Applied Technology Council Redwood, CA.

ATC, 2002a. *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook*, Applied Technology Council, Redwood City, CA.

ATC, 2002b. *Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation*, Applied Technology Council, Redwood, CA.

ATC, 2005. *Improvement of Nonlinear Static Seismic Analysis Procedures (FEMA 440)*, Applied Technology Council, Redwood, CA.

Coburn, A. and R. Spence, 2002. *Earthquake Protection*, John Wiley & Sons, Chichester.

NRC-IRC, 1992. *Manual for Screening of Buildings for Seismic Investigation*, Institute for Research in Construction - National Research Council of Canada, Ottawa, ON.

INIBS, 2003. *Earthquake Loss Estimation Methodology, HAZUS-MH MR1 Technical and User's Manual*, National Institute of Building Sciences, Washington, D.C.

LeBoeuf, D. and Nollet, M.-J., 2006. *Microzonage et vulnérabilité sismique de la ville de Québec 2005-2006*, for the City of Québec, July 17, 2006, 108 pp.

Onur, T., 2001. Seismic Risk Assessment in South-western British Columbia, *Ph.D. Thesis,* University of British Columbia**,** Vancouver.

Powell, G. H., 2006. *Static Pushover Methods - Explanation, Comparison and Implementation*, 8th U.S. National Conference on Earthquake Engineering, San Francisco, California.

Sandi, H., 1982. *Seismic vulnerability and seismic intensity*, 7th European Conf. on Earthquake Engineering, Athens.