Development of a Seismic Vulnerability Assessment Method for Schools in Eastern Canada

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SUMMARY:
The paper describes the development of a rapid seismic screening method for school buildings and its application to the province of Québec, located in Eastern Canada, a region of moderate seismicity. The method is a score assignment procedure, with scores calculated based on the capacity spectrum method. The final score of a building depends on the seismicity, lateral load resisting system, construction year, height, local soil conditions, structural weaknesses (horizontal and vertical irregularities, deterioration and short concrete columns) and potential for pounding. The method was applied to 101 public school buildings located in the city of Montréal and compared with other existing methods. For this sample, most of the parameters considered for the calculations influenced the final scores, and the method is able of classifying buildings in accordance with the severity of irregularities and potential pounding, both key aspects in the assessment of school buildings due to the high predominance of these features.

Keywords: Rapid seismic screening, schools, capacity spectrum method.

1. INTRODUCTION

Seismic vulnerability assessment methods based on rapid visual screening or score assignment procedures are intended to be coarse screening procedures using little resources per building. This is achieved by evaluating a limited number of features that influence the seismic performance and assigning an overall score or state of vulnerability to each building. The aim of the methods is to serve as an initial screening tool when a large inventory of buildings needs to be evaluated, so that further resources can be invested in the examination of only those buildings deemed critical. An ideal screening method will identify all the buildings that are potentially seismically hazardous, while limiting the number of safe buildings that will unnecessarily be tagged to undergo a more detailed evaluation (NZSEE, 2006). It was found that existing seismic screening methods for buildings in North America, namely the Canadian *Manual for Screening of Buildings for Seismic Investigation*, NRC92 (NRC/IRC, 1992), and the U.S. *Rapid Visual Screening of Buildings for Potential Seismic Hazard*, presented in the FEMA154 report (ATC, 2002), were not well adapted to the evaluation of school buildings in eastern Canada (Tischer et al., 2011). The first issue is that NRC92 needs updating to include the latest uniform seismic hazard data for the region, introduced in the 2005 edition of the National Building Code of Canada (NBC), and FEMA154 was developed for the United States and needs to be modified to be applicable in Canada. The second issue is that these methods were developed for the general building stock while school buildings typically have special characteristics such as structural irregularities and insufficient separation joints with adjacent buildings. Improved treatment of these characteristics should be included because they make schools especially vulnerable.

The study of a sample of 101 public school buildings in the city of Montréal, Québec, complemented with a literature review, confirmed that schools tend to be low-rise structures using a limited number of lateral load resisting system types (LLRS). On the one hand, this implies that reduced diversity in construction types will simplify the seismic assessment procedure, but on the other hand, the LLRS type alone will no longer be a sufficient parameter for the differentiation of the seismic vulnerability.

As for construction years, they follow demographic growth and political changes. The typical Québec school is also not recent in construction (1970s and before), having therefore strength and ductility deficiencies due to the lack of adequate seismic design criteria used at the time. The high incidence of structural features that could compromise seismic safety was confirmed, with 80% of the buildings examined having at least one type of irregularity.

The proposed seismic screening method addresses the shortcomings of existing North American methods and was developed specifically for school buildings located in Québec (Tischer, 2012). The method is a score assignment procedure following the FEMA154 methodology, with scores calculated based on the capacity spectrum method. Its application relies on a data collection form to be completed during visual inspection of a building, complemented with the study of building plans and other sources of information whenever possible. Initially, the seismicity has to be classified according to three severity levels, low, moderate or high. Then the LLRS has to be identified (and confirmed by visual inspection) and related to one of the 15 predefined building types listed in Table 1.1. A basic structural hazard score (BSH) is assigned to each building type for each seismicity level. To consider specific characteristics of the building that could affect its seismic performance, the score is then altered by adding or subtracting score modifiers to obtain the final structural score. The final score is related to the probability of the building to collapse, with higher final scores indicating a better seismic performance. Table 1.2 shows the ranking proposed for the classification of the buildings, from very high to low priority for future interventions, where possible score values are between -2.1 and 7.2.

Table 1.1. LLRS building types, adapted from (NRC/IRC, 1992) and (ATC, 2002)

LLRS Type (NRC92)	**FEMA154 Denomination**	**Description**
WLF	W1	Wood light frame
WPB	W2	Wood, post and beam
SMF	S1	Steel moment resisting frame
SBF	S2	Steel braced frame
SLF	S3	Steel light frame
SCW	S4	Steel frame with concrete shear walls
SIW	S5	Steel frame with infill masonry shear walls
CMF	C1	Concrete moment resisting frame
CSW	C2	Concrete shear walls
CIW	C3	Concrete frame with infill masonry shear walls
PCW	PC1	Precast concrete walls
PCF	PC2	Precast concrete frame
RML	RM1	Reinforced masonry bearing walls with wood or metal deck floors or roofs
RMC	RM2	Reinforced masonry bearing walls with concrete diaphragms
URM	URM	Unreinforced masonry bearing walls

Table 1.2. Ranking of final scores of the adapted seismic screening method, from (McConnell, 2007)

Priority for future intervention	**Probability of collapse**	**Final Score**
Very high	100%	≤ 0.0
High	10% to 100%	0.1 – 1.0
Moderate	1% to 10%	1.1 – 2.0
Low	Below 1%	> 2.0

2. GENERAL PROCEDURE FOR THE CALCULATION OF SCORES

The calculation of the BSHs and score modifiers relies on seismic analysis of simple benchmark models deemed representative of each LLRS type. The BSH is defined as the negative of the decimal logarithm of the probability of collapse of the building given a ground motion corresponding to the maximum considered earthquake, P(collapse given MCE):

$$\mathrm{BSH} = -\log_{10}[\mathrm{P(collapse\ given\ MCE)}] \tag{2.1}$$

To solve Eqn. 2.1, first the maximum spectral displacement (dpi) is estimated using the capacity spectrum method, a nonlinear static analysis procedure described in FEMA440 (ATC, 2005) and shown in graphical form in Fig. 2.1. This method assumes that the maximum inelastic deformation of a nonlinear single-degree-of-freedom (SDOF) system can be estimated from the maximum elastic deformation of an equivalent linear elastic SDOF which has natural period and viscous damping ratio values (T_{eq} and β_{eq}) higher than the nonlinear system (T_o and β_o). The inputs of the method are the lateral force-deformation relationship of the structure, commonly known as the push-over or capacity curve, and the seismic load demand. Both are plotted in the form of spectral acceleration (S_a) vs. spectral displacement (S_d) curves. In this format natural periods can be represented by radial lines through the origin. The equivalent period (T_{eq}) is assumed to be the secant period at the intersection of the capacity curve and the seismic demand curve with reduced equivalent damping. The equivalent damping (β_{eq}) is estimated based on the ductility, related to the area under the capacity curve up to dpi. Since both T_{eq} and β_{eq} depend on the estimated dpi, an iterative process is necessary to calculate β_{eq}.

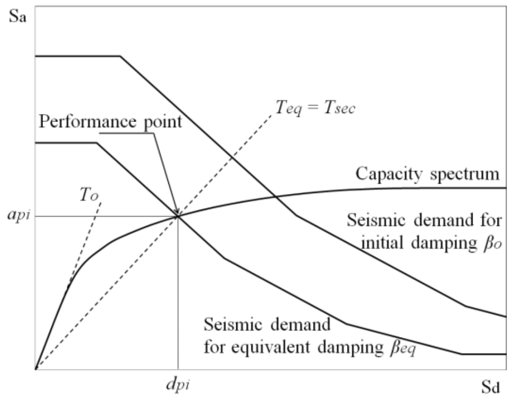

Figure 2.1. Capacity spectrum method, adapted from (ATC, 2005)

After obtaining dpi, the probability of a LLRS building type to be in a complete damage state, P(complete|dpi) is then determined from fragility curves for the benchmark models using dpi as input. Finally, the probability of collapse is defined as P(complete|dpi) times the estimated fraction of the buildings in complete damage state[1] that are expected to collapse in similar conditions (collapse rate), as given in Eqn. 2.2. Each LLRS model building type is described by generic capacity curves, fragility curves and collapse rates from *Hazus-MH MR4 Technical Manual* (NIBS, 2003).

$$\mathrm{P(collapse\ given\ MCE) = P(complete|dpi) \cdot collapse\ rate} \tag{2.2}$$

Taking into consideration the specific characteristics of school buildings, score modifiers for building height, construction year, structural weaknesses (irregularities in plan and elevation, deterioration and presence of short concrete columns), potential for pounding and local soil conditions were obtained. To determine the score modifier for each case, first interim scores were calculated following the same procedure as for the BSHs, the only difference being that the input capacity or acceleration spectra were modified to consider the desired feature. The score modifier was then obtained by subtracting the interim scores from the corresponding BSH.

3. INPUT PARAMETERS

3.1. Seismic zoning

For the developed method, the province of Québec was classified into three seismic regions, of high,

[1] Complete damage state is defined as a building that has collapsed or is in imminent danger of collapse due to failure of its structural elements. It implies that the structure must be replaced.

moderate and low seismicity. To select the parameter that defines each zone, it must be considered that in Canada, seismic hazard is determined based on spectral acceleration (Sa) values with 2% probability of exceedance in 50 years; values are published for several locations at periods of 0.2s, 0.5s, 1.0s and 2.0s, considering 5% viscous damping and reference soil class C, corresponding to soft rock or very dense soil with a shear wave velocity in the top 30m between 360 and 760m/s. School buildings are typically low-rise, and therefore only short and intermediate period responses are influential when evaluating their response. More specifically, when applying the capacity spectrum method the most relevant S_a value should be the one closest to the effective period of the structure. From the analysis of a large number of cases it was determined that effective period values are typically between 0.5 and 0.7s. It follows that S_a(0.5s) is most relevant, and this parameter was therefore selected to define the seismic zones.

To select limiting values for the three seismic zones two conditions were considered. First, the different categories ought to be relevant given the province's particular seismic hazard distribution and its relation to the demographics. Second, the variation of BSHs for a given bracket of spectral acceleration values should be limited. Seismic hazard in Québec is extremely varied. The northern region, covering more than 70% of the province's approximately 1.5 million km^2 territory, has a very low seismicity. The Saint Lawrence and Ottawa Valley regions to the south are the province's most active seismic zones, with a seismicity level that is moderate. These are the province's most densely populated regions as well. A very small (approximately 60km radius) and luckily sparsely populated region is highly active in the Charlevoix region. Based on statistical data of the 2006 Canadian census, the population distribution for different seismicity levels was defined. S_a values as given by the 2010 edition of the National Building Code of Canada (NBC) (NRC/IRC, 2010) were determined for all cities with a population over 10,000, accounting for 75% of the province's total population. BSHs were calculated for several seismicity levels, considering increments of 0.05g of S_a(0.5s) values. Based on the results, S_a values were then grouped in three seismic zones defined in Table 3.1. To calculate the S_a values for each seismicity region, the weighted mean values with respect to the population were used.

Table 3.1. Spectral acceleration values for each seismic zone

Seismicity	Limiting values [g]	Sa(0.2s) [g]	Sa(0.5s) [g]	Sa(1.0s) [g]	Sa(2.0s) [g]
High	Sa(0.5s) > 0.35	0.79	0.45	0.20	0.07
Moderate	Sa(0.5s) = 0.25 to 0.35	0.62	0.30	0.14	0.05
Low	Sa(0.5s) < 0.25	0.55	0.13	0.06	0.03

3.2. Characterization of buildings

Sets of capacity and fragility curves identified as High-Code, Moderate-Code, Low-Code and Pre-Code capture the variability of strength and ductility for each LLRS type for each target seismicity level. To capture the behaviour of older buildings, designed under less stringent seismic provisions, a lower seismic design level was assigned to them. Therefore an appropriate building characterization will depend on two factors: the seismicity of the site and the construction year of the building, related to the seismic provisions used in design. The selected damage functions are shown in Table 3.2. It was deemed that historically the design practices for moderate and high seismic zones in the province are comparable, actually a very small region (Charlevoix) is highly seismic so both levels are grouped together for damage function assignment. To assess if the generic capacity curves used are appropriate for school buildings in Québec, fundamental periods of school buildings located in Montréal, obtained from ambient vibration measurements, were compared to the linear elastic part of the capacity curves with good agreement (Tischer et al., 2012).

Table 3.2. Damage functions for seismic screening in Eastern Canada

Seismicity	Post-Benchmark (1990)	1970-1990	Pre-Code (1970)
Moderate and High	Moderate-Code	Low-Code	Pre-Code*
Low	Low-Code	Pre-Code*	Pre-Code*

* WLF: Low code

In Canada the NBC is updated approximately every five years, and the benchmark years of Table 3.2 were selected based on the evolution of the seismic provisions for new buildings. The year 1970 was chosen as the Pre-Code year for all LLRSs mainly based on the introduction of the first probabilistic seismic zoning map. The 1953 NBC where seismic provisions first appeared was disregarded because of the qualitative nature of the seismic map and the discontinuous changes in adjacent zones in Eastern Canada. The year 1970 was also the first time when the fundamental period of the structure was considered in the calculation of the lateral seismic force. The Post-Benchmark year was defined as 1990, based mainly on the improvement in ductility requirements for structural steel and reinforced concrete buildings. Although some ductility requirements were already included in earlier editions of the code, only in 1990 was a clear link made between the NBC and the Canadian Standards Association (CSA) materials design standards, assuring that the ductility required by 1990 NBC was effectively achieved in practice. The seismic zoning had also been updated in 1985, increasing the return period of the maximum design earthquake from 100 to 475 years.

It can be argued that the Post-Benchmark year can be further refined by LLRS type. For ductile concrete moment frame structures, for example, design and detailing provisions were introduced as early as 1977. One uniform date was preferred for simplicity, considering that the Post-Benchmark year has low significance in the screening process of schools in Québec. According to a school inventory report from the Québec Ministry of Education (Chagnon, 2006), around 75% of them were constructed prior to 1970 and therefore are assigned the Pre-Code damage functions.

4. DEVELOPMENT OF THE BASIC STRUCTURAL HAZARD SCORES AND SCORE MODIFIERS

4.1. Basic Structural Hazard Scores (BSHs)

To calculate the BSHs presented in Table 4.1, soil type C, capacity curves for low rise buildings and seismic design levels for buildings constructed between 1970 and 1990 (see Table 3.2) were considered. Initial damping used for the application of the capacity spectrum method was 5% for all cases. Deviation from these characteristics are considered by the score modifiers.

Table 4.1. Basic structural hazard scores (BSHs)

LLRS	**Seismic Zone**		
Type	**Low**	**Moderate**	**High**
WLF	5.2	4.3	3.7
WPB	5.7	4.7	4.1
SMF	4.7	3.2	2.8
SBF	4.7	3.7	3.2
SLF	4.6	3.6	3.1
SCW	4.6	3.7	3.1
SIW	4.4	3.5	3.0
CMF	4.3	3.3	2.7
CSW	4.6	3.6	3.0
CIW	4.0	3.1	2.6
PCW	4.3	3.2	2.7
PCF	3.5	3.3	2.6
RML	4.2	3.6	3.0
RMC	4.3	3.7	3.0
URM	2.6	2.5	2.1

4.2. Score modifiers

Score modifiers were obtained for building height, construction year, potential structural deficiencies (horizontal and vertical irregularities, deterioration and short concrete columns), potential for pounding of adjacent buildings and local soil conditions. For the calculation of mid-rise building score modifiers, presented in Table 4.2, interim scores were calculated with the provided capacity and fragility curves for mid-rise buildings where applicable, keeping the same seismic design levels.

Two sets of score modifiers were calculated to consider the construction year: Pre-Code and Post-Benchmark, presented in Table 4.3. To calculate the interim scores, the same input parameters as for the BSHs were used, only modifying the seismic design level to account for the construction year, as specified in Table 3.2. For the consideration of local soil conditions, score modifiers were calculated using the 2010 NBC soil types A (hard rock) to E (soft soil) by applying the corresponding ground motion amplification factors for short and long periods to the acceleration spectra. Results are presented in Table 4.4. Since soil class C is considered as a benchmark for the BSHs, the score modifier for it is 1.0. Structures located on soil type F (poor soil with high potential for liquefaction) cannot be addressed by the screening method, and should be evaluated in consultation with a geotechnical engineer experienced in earthquake engineering.

Table 4.2. Score modifiers for mid-rise buildings

LLRS Type	**Seismic Zone**		
	Low	**Moderate**	**High**
WLF	N/A	N/A	N/A
WPB	N/A	N/A	N/A
SMF	0.4	0.3	-0.3
SBF	0.0	-0.1	-0.2
SLF	N/A	N/A	N/A
SCW	0.2	0.0	0.0
SIW	0.1	0.0	-0.1
CMF	0.2	0.1	-0.1
CSW	0.1	0.0	0.0
CIW	0.0	0.0	0.1
PCW	N/A	N/A	N/A
PCF	0.1	0.1	-0.1
RML	0.0	-0.1	0.3
RMC	0.0	-0.1	0.2
URM	0.4	0.5	1.5

Table 4.3. Score modifiers for Pre-Code and Post-Benchmark buildings

LLRS Type	**Pre-Code**			**Post-Benchmark**		
	Low Seismicity	**Moderate Seismicity**	**High Seismicity**	**Low Seismicity**	**Moderate Seismicity**	**High Seismicity**
WLF	N/A	0.0	0.0	0.0	0.0	0.0
WPB	N/A	-0.3	-0.3	0.4	0.6	0.5
SMF	N/A	0.0	0.0	0.0	1.1	0.8
SBF	N/A	-0.3	-0.3	0.4	0.7	0.6
SLF	N/A	-0.3	-0.2	0.3	0.5	0.4
SCW	N/A	-0.3	-0.3	0.4	0.7	0.6
SIW	N/A	-0.3	-0.3	0.4	N/A	N/A
CMF	N/A	-1.0*	-0.3	0.4	0.8	0.6
CSW	N/A	-0.3	-0.2	0.3	0.9	0.8
CIW	N/A	-1.0*	-0.3	0.4	N/A	N/A
PCW	N/A	-0.6	-0.4	0.8	0.0	0.0
PCF	N/A	-0.2	-0.2	0.2	0.9	0.7
RML	N/A	-0.4	-0.3	0.5	0.2	0.4
RMC	N/A	-0.4	-0.3	0.5	0.2	0.4
URM	N/A	-0.4	-0.3	0.5	N/A	N/A

* Values modified based on judgment from -0.3 to -1.0, as suggested by (ATC, 2002).

Table 4.4. Score modifiers for soil types A, B, D and E

LLRS	Low Seismicity				Moderate Seismicity				High Seismicity			
Type	A	B	D	E	A	B	D	E	A	B	D	E
WLF	0.7	0.5	-0.4	-0.9	0.8	0.5	-0.4	-1.0	0.8	0.4	-0.4	-0.8
WPB	1.1	0.8	-0.5	-1.1	1.2	0.9	-0.5	-1.1	1.2	0.5	-0.4	-1.0
SMF	1.3	0.9	-0.6	-1.2	0.9	0.6	-0.3	-0.8	0.8	0.4	-0.3	-0.6
SBF	1.0	0.7	-0.4	-1.0	1.1	0.8	-0.4	-1.0	1.1	0.5	-0.4	-0.9
SLF	1.1	0.7	-0.4	-1.0	1.1	0.8	-0.4	-0.9	1.1	0.5	-0.3	-0.8
SCW	0.9	0.6	-0.4	-1.1	1.1	0.8	-0.5	-1.1	1.1	0.6	-0.4	-0.9
SIW	0.9	0.6	-0.4	-1.0	1.1	0.8	-0.4	-1.0	1.1	0.5	-0.4	-0.9
CMF	0.9	0.7	-0.6	-1.1	1.2	0.7	-0.5	-1.0	1.0	0.5	-0.3	-0.8
CSW	1.0	0.7	-0.4	-1.1	1.1	0.8	-0.4	-1.1	1.1	0.5	-0.4	-0.9
CIW	0.9	0.6	-0.4	-1.0	1.1	0.8	-0.4	-1.0	1.1	0.5	-0.4	-0.9
PCW	0.9	0.6	-0.3	-0.7	0.9	0.6	-0.5	-1.1	1.0	0.6	-0.3	-0.8
PCF	1.0	0.7	-0.4	-1.1	1.1	0.8	-0.4	-1.0	1.1	0.5	-0.4	-0.9
RML	1.0	0.7	-0.4	-0.9	1.0	0.6	-0.6	-1.2	1.1	0.6	-0.4	-0.9
RMC	1.0	0.7	-0.4	-0.9	1.0	0.7	-0.6	-1.2	1.1	0.6	-0.4	-1.0
URM	0.4	0.3	-0.2	-0.5	0.6	0.4	-0.3	-0.7	0.6	0.3	-0.3	-0.6

Due to the prevalence of structural irregularities and other features that could adversely affect seismic performance, now called "structural weaknesses" as a more general term, their treatment was significantly modified compared to FEMA154. Four separate types of weakness were considered: horizontal irregularities, vertical irregularities, deterioration (presumably due to improper maintenance) and short concrete columns. The effect of each type on the seismic performance was classified as severe, significant or insignificant, as in the New Zealand rapid seismic assessment method (NZSEE, 2006). To provide guidance on the selection of the severity level of the four structural weaknesses, an illustrated user's guide was developed (Tischer, 2012).

To account for the effect of structural weaknesses in a simple manner as needed for rapid seismic screening is not an easy task because the possible defects are so varied, and many parameters influence the building's response. The selected approach was adapted from FEMA154's treatment of horizontal irregularities, characterizing a given structural weakness as an increase of the spectral acceleration values in the calculation of the interim score. Significant irregularity modifiers were calculated using 150% spectral acceleration values, as proposed for horizontal irregularities in FEMA154. For severe irregularities an increase of 350% was used, so that the average values of the modification factors would be the same as the average of the vertical irregularity modifiers of FEMA154 (considered the most severe type of irregularity by FEMA154). Score modifiers for structural weaknesses can be found in Table 4.5, where the columns marked as $1.5S_a$ correspond to significant effects and the columns marked as $3.5S_a$ to severe effects. Note that insignificant effects have no score modifier associated with them.

Guidance for the treatment of potential pounding of adjacent buildings, ignored in FEMA154 , was also taken from the seismic screening method developed by New Zealand Society for Earthquake Engineering (NZSEE, 2006). As for structural weaknesses, the potential for pounding was classified as severe, significant or insignificant. The severity was determined by comparing the separation between buildings, d, to limiting values related to the building height, h. The resulting cases are: for $d < 0.005h$ severe effect, for $0.005h < d < 0.01h$ significant effect, and for $d > 0.01h$ insignificant effect on seismic performance was considered. Furthermore, floor misalignment in separate adjacent buildings was identified as an aggravating factor. For vertical misalignment greater than 20% of the storey height, an increase of $3.5S_a$ was used for severe, $1.5S_a$ for significant and $1.3S_a$ for insignificant effects on the seismic performance. For vertical misalignment lower or equal to 20% of the storey height, an increase of $1.5S_a$ was used for severe, $1.3S_a$ for significant and $1.0S_a$ for insignificant effects on seismic performance. As for structural weaknesses, score modifiers were calculated based on an interim score obtained by these increased seismic demands. Score modifier values for each case are the same as given in Table 4.5.

Table 4.5. Score modifiers for structural weaknesses and pounding effects

LLRS Type	Seismicity								
	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
	1.3 Sa			1.5 Sa			3.5 Sa		
WLF	-0.4	-0.4	-0.4	-0.6	-0.6	-0.6	-1.5	-1.6	-1.5
WPB	-0.4	-0.5	-0.4	-0.6	-0.6	-0.6	-1.9	-1.8	-1.6
SMF	-0.4	-0.3	-0.3	-0.7	-0.4	-0.4	-1.8	-1.2	-1.0
SBF	-0.3	-0.3	-0.4	-0.5	-0.6	-0.6	-1.7	-1.6	-1.4
SLF	-0.3	-0.3	-0.3	-0.5	-0.5	-0.5	-1.7	-1.5	-1.2
SCW	-0.3	-0.4	-0.4	-0.5	-0.7	-0.6	-1.8	-1.7	-1.4
SIW	-0.3	-0.3	-0.4	-0.5	-0.6	-0.6	-1.7	-1.6	-1.4
CMF	-0.4	-0.4	-0.3	-0.7	-0.6	-0.5	-1.8	-1.6	-1.3
CSW	-0.4	-0.4	-0.4	-0.5	-0.6	-0.6	-1.8	-1.7	-1.5
CIW	-0.3	-0.3	-0.4	-0.5	-0.6	-0.6	-1.6	-1.6	-1.4
PCW	-0.3	-0.5	-0.3	-0.4	-0.7	-0.5	-1.4	-1.6	-1.4
PCF	-0.3	-0.3	-0.4	-0.5	-0.6	-0.6	-1.8	-1.7	-1.3
RML	-0.3	-0.5	-0.4	-0.5	-0.7	-0.6	-1.6	-1.8	-1.5
RMC	-0.4	-0.5	-0.4	-0.5	-0.7	-0.6	-1.6	-1.9	-1.5
URM	-0.2	-0.3	-0.3	-0.3	-0.4	-0.4	-0.8	-1.1	-0.9

5. APPLICATION OF THE METHOD

The adapted seismic screening method was tested by applying it to 101 individual school buildings at 16 different school sites. These schools were all located in Montréal, and are designated as emergency shelters for the city. Results showed 18 school buildings having very high priority for future interventions, 18 with high priority, 44 with moderate priority and 21 with low priority (see Table 1.2 for more information of interpretation of this classification), with an average final score of 1.3. A high standard deviation of 1.2 on the final scores shows how the proposed method is capable of differentiating between the buildings evaluated, which is a desirable feature for screening.

The influence of the BSHs and score modifiers on the classification of the buildings was determined by performing analysis of variance (ANOVA) on the numerical values obtained for each of them, excluding score modifiers where the number of available cases was too low for statistical significance. Results showed that the BSHs cannot be differentiated between groups, and are therefore not influential in the classification of the buildings. This result was expected because of the limited number of LLRS building types in the pool of buildings and the low variability of the BSHs values for the few predominant LLRS types: the BSH values are concentrated in the narrow range between 3.1 and 3.6 for 96% of the total number of buildings studied. However, most of the other parameters showed a high influence on the final score, including the pre-code, horizontal irregularities, vertical irregularities and potential for pounding modifiers. Fig. 5.1 illustrates two key score modifiers, horizontal and vertical irregularities, showing their distribution according to their effect for the different priority classes for intervention.

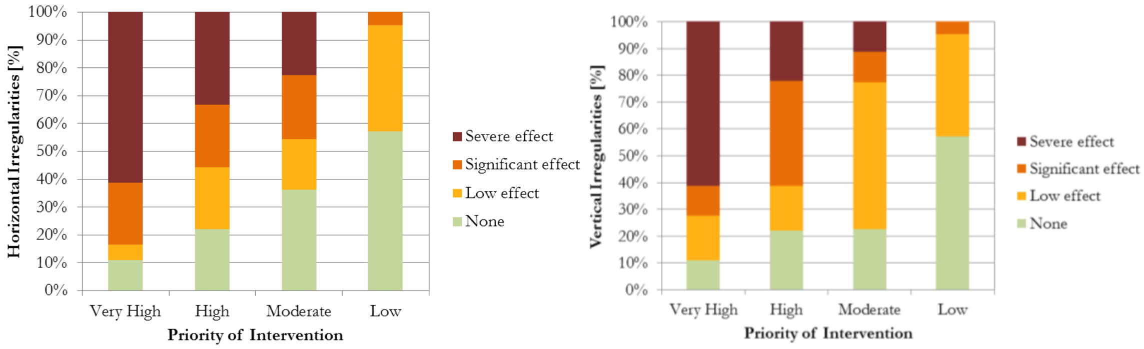

Figure 5.1. Distribution of horizontal and vertical irregularities according to their effect on the final score

6. COMPARISON WITH EXISTING METHODS

To highlight the advantages of the proposed method when compared with existing procedures, scores were also calculated using FEMA154 and NRC92. Average and standard deviations obtained with the adapted seismic screening method and FEMA154 are very close. However, such a direct comparison is questionable, since FEMA154 does not consider pounding and deterioration. When scores obtained with the proposed seismic screening method were recalculated without considering these two modifiers for a more realistic comparison, clearly higher scores were achieved by this method with a consistent building-by-building agreement, as can be seen in Fig. 6.1. The less conservative results obtained with the adapted method can be explained by several factors, including the higher BSHs obtained because of the update of the underlying capacity spectrum method, the less penalizing score modifier for moderate effects of vertical irregularities and the inappropriate soil classification of FEMA154 when applied to Canada. Comparison between the adapted screening method and NRC92 is not as straight forward, since they are different in methodology and final score values. However, they can be compared based on the classification of the final score according to the priority of future intervention. In general terms the proposed method is more conservative than NRC92 for the buildings studied, but the building-by-building agreement is very poor, see Fig. 6.1. The scatter between the results can be explained by the different parameters that single out critical buildings for both cases.

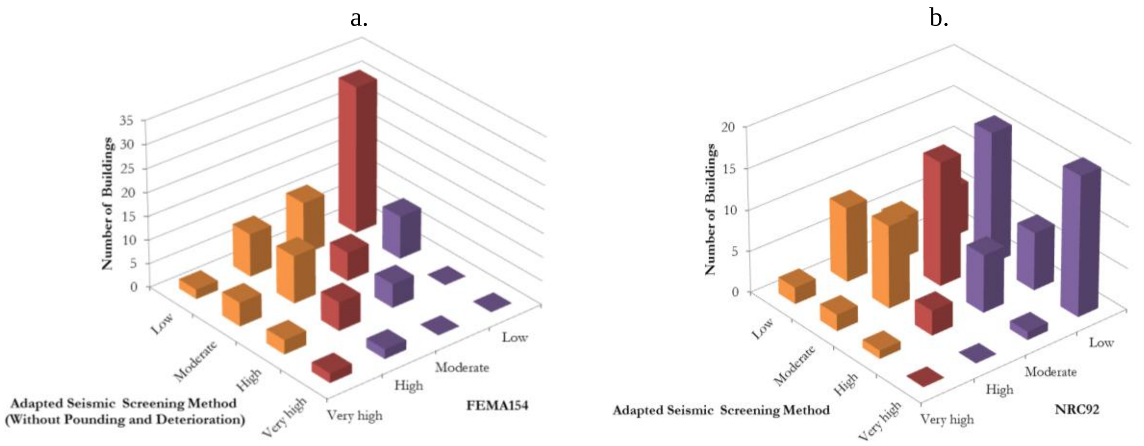

Figure 6.1. Distribution of building classification for the adapted seismic screening method compared to (a) FEMA154 and (b) NRC92

The influence of the different parameters that make up the final score of FEMA154 and NRC92 was also analysed using ANOVA. It was shown that FEMA154 does not properly capture the adverse effects of vertical and horizontal irregularities. FEMA154 is extremely penalizing when vertical irregularities are present, and is incapable of discerning the severity of this irregularity: no building with a vertical irregularity was classified as having a low priority, and only two as having a moderate priority. Plan irregularities on the other hand, even when severe, have no influence on the final score. These FEMA154 shortcomings in dealing with irregularities are very significant when evaluating schools, where they are extremely common. General results of the ANOVA of the parameters that make up the final score of NRC92 (seismicity, soil conditions, type of structure, irregularities, importance and non-structural hazards) indicate that each one of these factors has a significant influence on the final score. This result is surprising in the case of seismicity since all the buildings evaluated are located in the same seismic zone (on the island of Montréal). Further examination of the results demonstrated that the NRC92 method systematically penalizes older buildings. Clearly pre-1970 buildings fare worse in the final score, with all buildings classified as having very high (potentially hazardous) or high priority for future intervention. When performing ANOVA for the LLRS type, presence of irregularities and non-structural hazard factors independently for pre- and post-1970 buildings, it was found that there is a clear difference between groups. For the irregularities factor however, there is no difference between groups for the pre-1970 buildings.

7. CONCLUSIONS

School buildings in general tend to be low-rise buildings of a limited number of lateral load resisting systems. Features that could compromise their seismic safety, such as vertical and horizontal structural irregularities, are extremely common. These particular characteristics are not adequately addressed by existing rapid seismic screening tools in Canada (NRC92) and United States (FEMA154). Therefore an adapted method for school buildings was developed for Québec. The method is a score assignment procedure, with the final score dependent on the seismicity, lateral load resisting system type, building height, construction year, potential structural weaknesses (horizontal and vertical irregularities, deterioration and short concrete columns), potential for pounding of adjacent buildings and local soil conditions. The methodology follows that of FEMA154, with scores calculated based on the capacity spectrum method. The proposed method better reflects the specific structural characteristics of school buildings and takes into consideration the province's seismicity and soil classification as stipulated in the 2010 edition of the NBC. The application of the method is relatively simple and based on a form that can be filled out relying only on visual inspection of a building, although inspection of building plans and use of other relevant sources of information are strongly recommended.

The application of the screening method to the sample of 101 school buildings and comparison with results from FEMA154 and NRC92 clearly highlight some advantages of the method developed. Analysis of the scores' variances confirms that most of the parameters evaluated are significantly influential on the final scores. In particular, the classification of the structural weaknesses and the potential for pounding according to their severity level proved effective in differentiating the likely seismic performance of the buildings, something not properly considered in existing methods.

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