Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 993

Assessing the post-earthquake functionality of critical buildings in Montréal

Ghyslaine McClure[1], Jordan Cappai[2], Richard Shapiro[3], Meng Li[4],
Guillaume Dunlop-Brière[2] and Pierre Keller[5]

ABSTRACT

The global seismic risk of the Montréal (Québec) area is rated as the second highest in Canada, after Vancouver (British Columbia). Although Montreal's seismic hazard as described in the National Building Code of Canada remains moderate, the risk is increased by the size of its population, the value of its urban infrastructure and the relative importance of its economic activity. Reducing urban seismic risk is a priority in Canada. The improvement of seismic safety and functionality of emergency preparedness centers, post-critical shelters and trauma and acute-care hospitals is a priority for Montréal's buildings. The evaluation of the seismic vulnerability of the operational and functional components (OFCs) of these facilities is an essential first step in risk assessment and mitigation planning for building functionality. OFC inspection visits have been conducted by the authors over the summer and fall 2009 in six hospitals (comprising 35 buildings) and 14 schools (comprising 91 buildings) designated as post-critical emergency shelters by the *Centre de sécurité civile de Montréal*. The data collected were analyzed and detailed risk assessment rating for individual components was established using the procedure described in the Canadian Standards Association document *CAN/CSA S832-06 Seismic risk reduction of operational and functional components (OFCs) of buildings*. The paper presents global statistics on seismic risk rating for the school and hospital buildings inspected.

1. Introduction

Owing to the development of robust seismic design standards for new buildings and efficient rehabilitation of existing buildings in high seismic areas, the experience of the last few decades has demonstrated that numerous buildings can sustain severe earthquakes with minimal damage to the structure itself. However loss of functions, serious safety risks and heavy non-structural damage continue to occur and are caused by failure of operational and functional components (OFC) such as mechanical, architectural and general content.

[1] Associate Professor, Dept. of Civil Engineering and Applied Mechanics, McGill University, Montréal, Canada
[2] Undergraduate summer research assistant, Dept. of Civil Engineering and Applied Mechanics, McGill University
[3] Undergraduate summer research assistant, Dept. of Mechanical Engineering, McGill University
[4] Undergraduate summer research assistant, School of Architecture, McGill University
[5] Visiting undergraduate research trainee, École Nationale des Sciences et Techniques Appliquées (ENSTA) de Paris, France.

Our assessment of the post-earthquake functionality of critical buildings on the island of Montréal was initiated a decade ago in collaboration with the *Centre de sécurité civile de Montréal* (Center of Civil Safety of the City of Montréal). Several post-critical facilities have been inspected since then and the results have been reported confidentially to direct stakeholders. Since May 2009, as part of the activities of the Canadian Strategic Research Network on Reducing Urban Seismic Risk, new evaluations have been conducted for 14 schools designated as emergency shelters by the *Centre de sécurité civile*, and for six hospitals in a pilot study conducted with the collaboration of *Agence de la santé et des service sociaux de Montréal* and the various hospitals. In total, 91 school buildings and 35 hospital buildings have been inspected.

The paper gives an overview of the post-critical building functionality project. After listing the objectives and outlining the methodology, we present a brief review of OFC classification and functionality requirements for emergency shelters and hospitals. Then the risk rating method based on the procedure suggested in *CAN/CSA S832-06 Seismic risk reduction of operational and functional components (OFCs) of buildings* (CSA 2006) is summarized. Global results and statistics are presented separately for schools and hospitals and, finally, some common OFC deficiencies observed in the facilities under evaluation are noted.

2. Objectives

The study involves five objectives:

1) Evaluate OFCs' vulnerability to damage and/ or failure along with the potential damages they can generate after a design-level seismic event in post-critical facilities such as hospitals and community schools designated as emergency shelters.
2) Inform the facility managers in charge about the high risk components.
3) Suggest mitigation measures in order to reduce the risk of the most vulnerable and important components.
4) Identify common functionality issues amongst hospitals and post-critical shelters in Montréal and inform the Center of Civil Safety of the City of Montréal as well as the buildings' major stakeholders (*Agence de la santé*, hospitals and school boards management).
5) Generate a feedback process with the technical committee of CSA S832 in order to improve the seismic risk rating method proposed in CAN/CSA S832-06.

3. Methodology

The global risk evaluation procedure for each facility comprises the following four steps:

1) Assessment of soil site effects using either seismic microzonation mapping or ground ambient noise measurements at the site;
2) Global screening of the building structure based on the study of structural plans and on-site inspections;
3) Structural identification of natural frequencies, mode shapes and internal damping with ambient noise measurements;
4) On-site inspection of OFC attachments and layouts and seismic risk rating.

Work is still in progress in the first three steps while the focus of this paper is the building functionality as evaluated in Step 4. Cooperation with the building's main technical stakeholders has been essential to assess the consequences of OFC failure or malfunction and to evaluate the global seismic risk. However, the study remains qualitative as it addresses solely OFC attachment layouts and position in the building without consideration of their internal functionality following strong shaking in the case of operational equipment. It is understood that internal functionality can only be guaranteed by the equipment manufacturer.

4. Classification of Operational and Functional Components

From a global standpoint, the various building components are divided between structural components which resist loads, and operational and functional components (OFCs) which make the building fulfill its functions and provide comfort and services to its occupants. Since the aim of the study was to evaluate the seismic risk of the OFCs only, the field team inspected the non-structural components following the classification provided in CAN/CSA S832-06. OFC inspection and risk rating responsibilities were shared among the participants according to their expertise and interests in civil engineering (general building characteristics and building common and specialized contents), mechanical engineering (mechanical, plumbing, electrical and information technology equipment) and architectural components.

5. Functionality Requirements of OFCs in Post-critical Facilities

In Canada, the seismic performance of buildings is specified in the National Building Code (NBC). Seismic design provisions for non-structural building components were first introduced in the 1953 NBC edition (NRC 1953) and covered acceleration-sensitive architectural components, towers and tanks. These provisions have evolved considerably until the 1995 edition (NRC 1995) and the current 2005 edition (NRC 2005) has brought only small changes. NBC 2005 Clause 4.1.8.17 covers several categories of non-structural components, elements of structures and equipment, with consideration of acceleration and displacement sensitivity. However, it is important to note that in reality these provisions had not been enforced in construction practice until very recently. As a result, most buildings that are deemed "earthquake-resistant" in Canadian urban areas are not necessarily adequate for post-seismic functionality. This remains a preoccupation, especially in a region with moderate seismic hazard like Montréal (this is similar in the Ottawa valley), where the design earthquakes are associated with severe ground accelerations.

The functionality requirements for buildings vary depending on their importance category and their use and occupancy. We are concerned here with hospitals and schools designated as emergency shelters. For hospitals, the following infrastructure and functions must be maintained immediately after an earthquake (CAN/CSA S832-06):

- Emergency medical equipment (life-saving equipment, life-support systems)
- Storage and distribution of medical gas
- Ventilation in areas subjected to airborne contaminants
- Medical files archives (access and confidentiality cannot be compromised)

The infrastructure and its essential services must be operational without interruption of:

- Emergency power and circuits
- Fire protection system (alarms, extinguishers and sprinklers)

- Natural gas supply
- Water system
- Sanitary system
- Communications system
- Heath, ventilation and air conditioning systems (HVAC)
- Interface infrastructure of public services (water, electricity, communication, gas, sewage)

Finally, for any post-critical emergency shelter the security of its occupants must remain a priority:

- OFCs that could injure or generate leaks of dangerous matter, explosions or fire must be safely restrained.
- Emergency exits and corridors must remain accessible at all times for safe egress.

6. Seismic Risk Rating Method for OFCs

The OFC risk rating method proposed by CAN/CSA S832-06 has been presented in some detail by Foo et al. (2007). It is based on the visual inspection of each typical OFC: only lightweight, non-dangerous or difficult to access components were exempted from the evaluation. Each component is assigned a Vulnerability Index, V, and a Consequence Index, C. The Vulnerability Index is determined with Table 6 of CAN/CSA S832-06, based on the following four vulnerability parameters: i) the type of restraint (full, partial or questionable, or no restraint); ii) the risk of impact and pounding of adjacent components; iii) the risk of overturning if the unrestrained component is somewhat slender; iv) and the relative flexibility of the component and its location in the building to recognize that flexible components are more prone to dynamic amplification than rigid ones and that seismic ground motion is generally amplified above ground floor level. In addition to these component parameters, the vulnerability is necessarily related to the seismic hazard at the building site and the fundamental sway frequency of the lateral load resisting system of the building.

The consequence Index, C, is related to the impact of the failure or malfunction of an OFC on the overall building functionality and on the safety of the occupants. It is determined using Table 7 of CAN/CSA S832-06. There are three main consequence parameters: i) the impact on life safety from malfunction or failure of the OFC during and immediately after the earthquake; ii) the consequences on the building functionality requirements as a function of building importance and occupancy – the performance objectives of the post-critical buildings covered here have been summarized above; iii) and property or asset protection.

The seismic risk index of a component, R, is the product of V and C; it provides a qualitative assessment of the risk level and allows priority setting for mitigation actions. As indicated in Table 1, the CAN/CSA S832-06 method has been calibrated such that R values of 15 or less represent OFCs with low risk for which mitigation is not required, while R values of 50 and above represent a high risk with necessary mitigation. The intermediate range 15 <R <50 represents the moderate risk level for which OFC mitigation is optional. It should be mentioned, however, that once mitigation action is decided, it is preferable to enhance the seismic resistance of the OFC so as to reach a low risk level, considering that mitigation costs are not usually sensitive to actual risk level.

Table 1. Seismic risk rating according to CAN/CSA S832-06

Risk Index, R	Risk Level	Mitigation
$R \leq 15$	Low	Not mandatory
$15 < R < 50$	Moderate	Optional
$R \geq 50$	High	Necessary

The seismic risk index alone does not provide a clear understanding of OFC mitigation and its advantages. Since OFC mitigation including structure retrofit and soil remediation are usually much more expensive than individual component risk mitigation; a retrofit index, RI, is used to determine the amount of component retrofit that can be completed in order to reduce the risk index to its lowest possible value. A high value of RI indicates that OFC mitigation effectively reduces the risk and vice versa for a low RI value. The calculation of RI is explained in CAN/CSA S832-06 and in Foo et al. (2007).

7. Local Site and Building Characteristics

Characteristics of Ground Motion and Soil Conditions, RG

The vulnerability index, V, requires the evaluation of a Ground index, RG, which combines seismic hazards and site effects, as indicated in Eq. (1):

$$RG = \{Fa\}\{Sa(0,2)\}/1,2 \tag{1}$$

According to Table C-2, Appendix C, Division B of NBC 2005, Montréal is assigned a uniform hazard spectral acceleration of 0.69g at period of 0.2 s, Sa(0.2), standardized with 5% critical damping. This spectral acceleration corresponds to a horizontal acceleration at the ground surface of 0.43g for a soil type C (stiff soil). Whenever available, we have used the information from the Montreal microzonation maps. Some ambient noise measurements have been made at specific hospital sites but this part of the work is still incomplete so more general information based on soil types was used as indicated in Table 4.1.8.4.B of NBC 2005.

Building Characteristics, RB

The Building Characteristics factor, RB, is established with Table 8 of CAN/CSA S832-06: it varies from 1.0 (for stiff low rise buildings on rock) to 1.5 (for buildings on soft or sensitive soils). RB values vary with the fundamental period of the building and the soil conditions at the site. When natural periods are not measured on site, and in the absence of better information, the natural period is roughly approximated as a function of number of stories, type of lateral load resisting system and number of floors. As mentioned previously, when ambient vibration measurements (AVM) had been made in hospitals, we have extracted the period values.

8. Risk Ratings for OFCs in Hospitals

Figure 1 summarizes the risk rating results for the 380 typical OFCs evaluated in the six hospitals of the study: 107 (27%) of them were rated as high seismic risk, while most (53%) were rated as moderate risk. The priority of our investigation is toward the high risk components since they require mitigation.

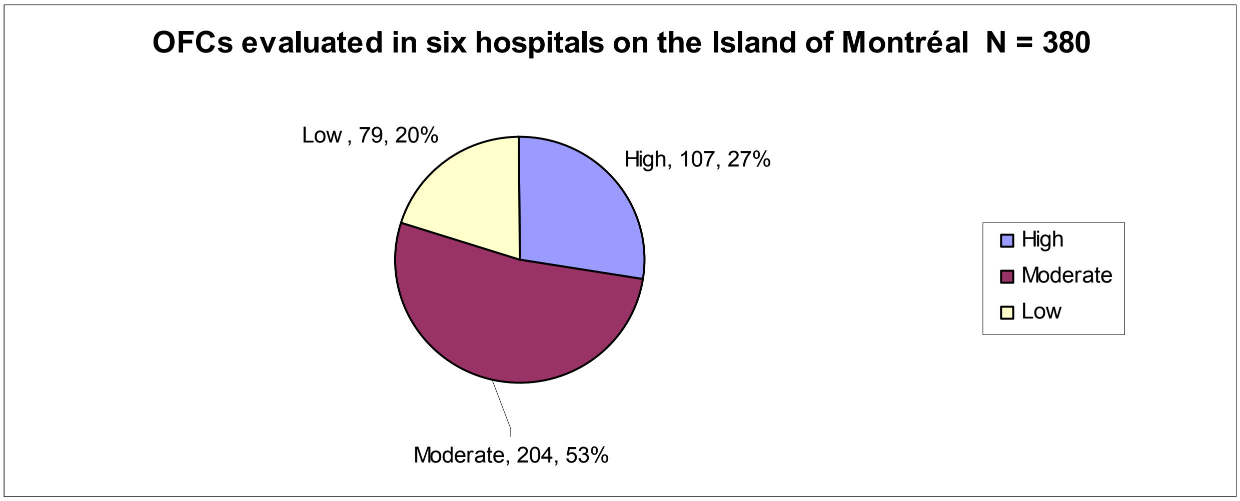

Figure 1. Seismic risk classification of 380 typical OFCs evaluated in six hospitals on the Island of Montréal.

Figure 2 presents more details on the types of high risk OFCs: a majority accounts for building services (58%) whereas building content accounts for 32%. Overall, mechanical services (MEC), electrical and information technology equipment (E&IT) and specialized medical content (SPE) were the most critical OFCs found in hospitals, counting respectively for 25%, 25% and 21% of the high risk components, as shown in Fig. 3. Lack of restraints was observed on mechanical OFCs such as emergency generators, sprinkler systems, elevator engines, boilers, chillers and portable fire extinguishers. Typically, emergency power generators are simply resting on the floor with no connection, and they lack horizontal restraint. When powered by batteries, batteries are not secured on their rack and can easily overturn, while the racks themselves are not restrained. Chillers installed on rooftops were equipped with vertical vibration isolators (often with damaged connections) but no lateral support. Many electrical rooms were found at risk: electrical control panels are typically tall and slender, thus prone to overturning. Most panels were unrestrained, neither at the base, nor at the top. Damage to electrical components poses a high risk of fire and most of the wall-mounted fire extinguishers were not adequately restrained either, suggesting that they could be damaged in their fall under strong shaking. Server rooms were vulnerable with unrestrained power supply batteries resting next to laterally unrestrained tall and slender server racks.

Specialized content is essential to the functionality of hospitals, mainly comprising medical equipment and apparatus, and medical archives. Research hospitals are also equipped with sensitive analysis devices and house valuable research specimens in free-standing unrestrained freezers or refrigerators. Often, mobile medical units on wheels are left in the corridors or next to patients. In many cases wheels are equipped with brakes that are not activated.

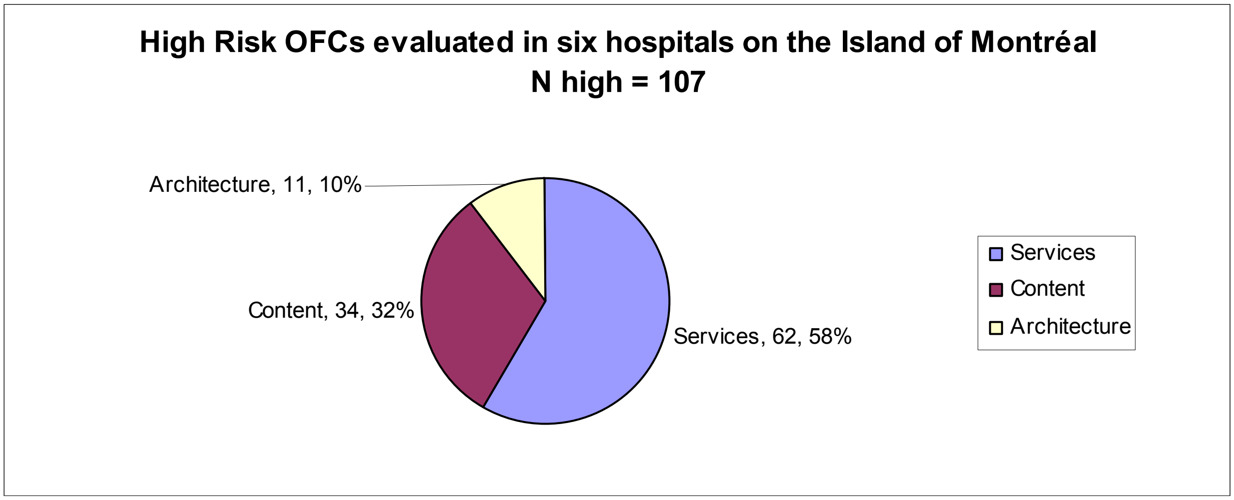

Figure 2. Classification of the 107 high risk hospital components according to their type (Architectural, Content and Building Services).

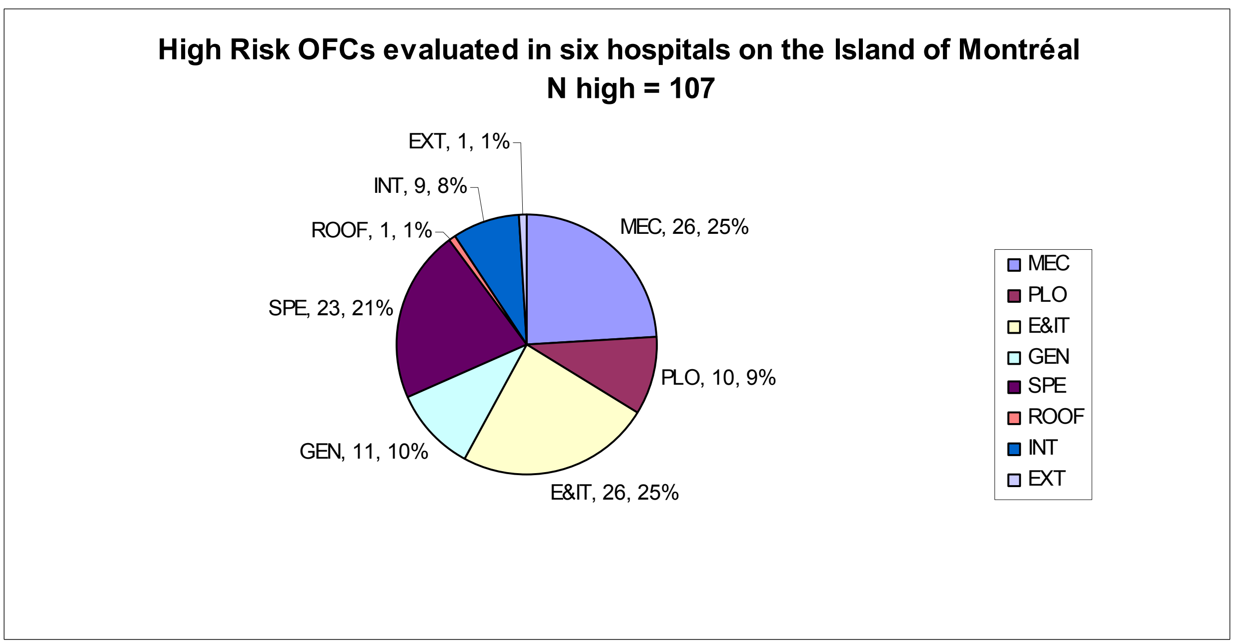

Figure 3. Detailed classification of the 107 high risk hospital components according to their specific function (MEC = Mechanical, PLO = Plumbing, E&IT = Electrical & Information Technology, GEN = General content, SPE = Specialized content, INT = Internal Architecture, EXT = External Architecture).

Although high risk architectural components may not appear important in number, some of them cover large building areas. In particular, several hospitals comprise laterally unrestrained suspended ceilings that pose a falling hazard during strong shaking. Moreover, some of these ceilings support relatively heavy lighting units that are unattached to the floor slab above. In such case, a falling ceiling can bring along light fixtures and sprinkler heads.

The retrofit indices, RI, calculated for the 107 high risk hospital components range from 31% to 100%, with 68 components having a RI above 60%. These numbers are conclusive; with such high retrofit indices, individual mitigation of high risk OFCs would greatly reduce their seismic risk. In fact, in most of the cases mitigation would simply consist in providing lateral bracing or replacing defective restraints. Since not all mobile medical equipment can be restrained for emergency purposes, simple docking or tether systems can be installed to limit their motion, thus reducing the risk of loss of function or the blockage of corridors and exits.

9. Risk Ratings for OFCs in School Buildings

Statistics are presented next for 12 of the 14 community schools designated as post-critical emergency shelters as complete results are still unavailable. A total number of 445 typical OFCs were evaluated from which 90 (20%) were rated as high risk, as shown in Fig. 4.

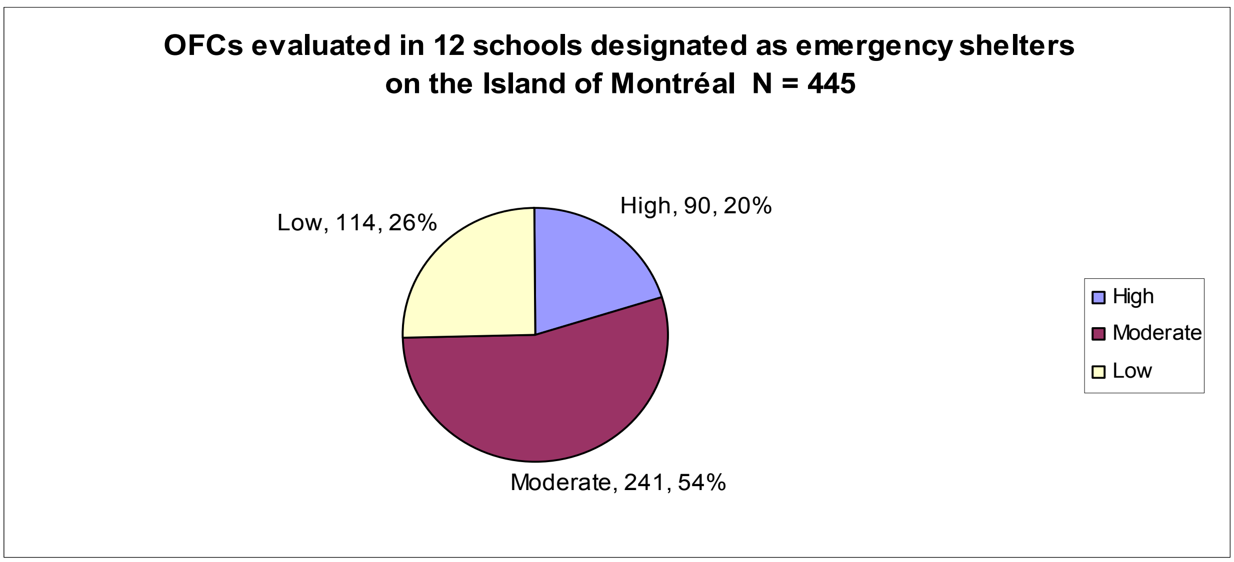

Figure 4. Seismic risk classification of 445 typical components evaluated in 12 public schools designated as emergency shelters on the Island of Montréal.

Figures 5 and 6 present more information about the 90 high risk OFCs identified in schools. It is seen that the majority of them (66%) account for building services: among these, the two main contributors are Mechanical components (MEC) for 30% of the total, and Electrical & Information Technology components (E&IT) for 27%.

The main OFC deficiencies observed in a majority of schools are the lack of adequate restraint for emergency generators, electrical control panels, portable fire extinguishers and boilers. Similar to hospitals, emergency power generators are simply resting on the floor with no restraint at all. Neither the batteries nor the racks are properly restrained, presenting the same issues mentioned earlier for high risk OFCs in hospitals.

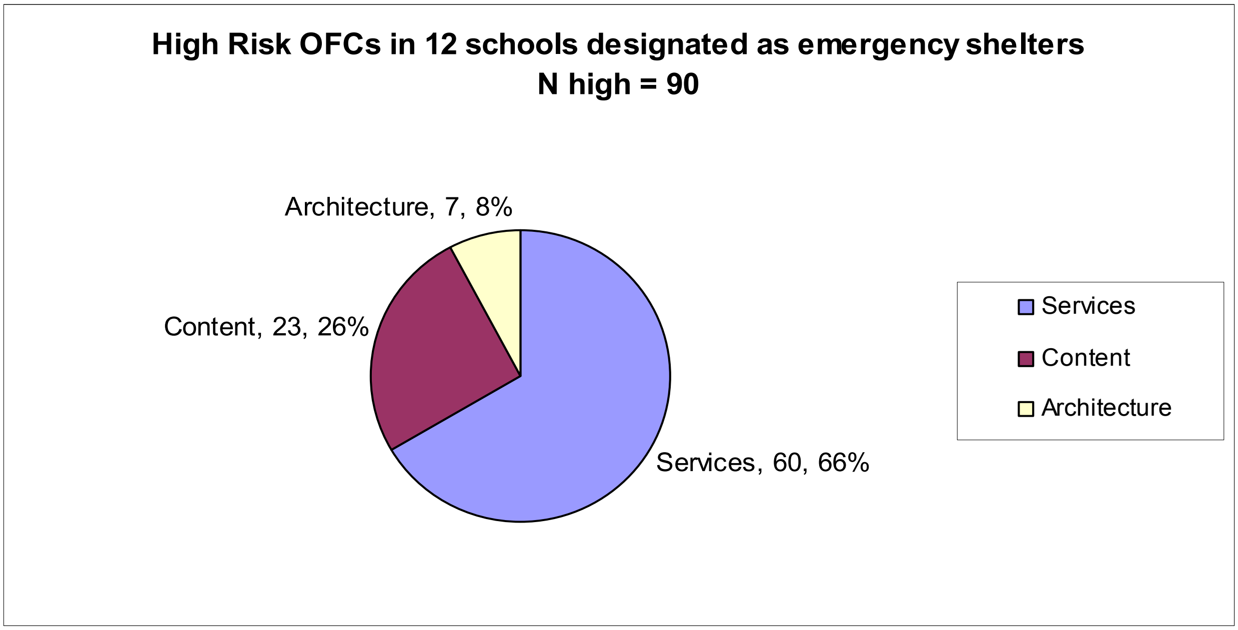

Figure 5. Classification of the 90 high risk school components according to their type (Architectural, Content and Building Services).

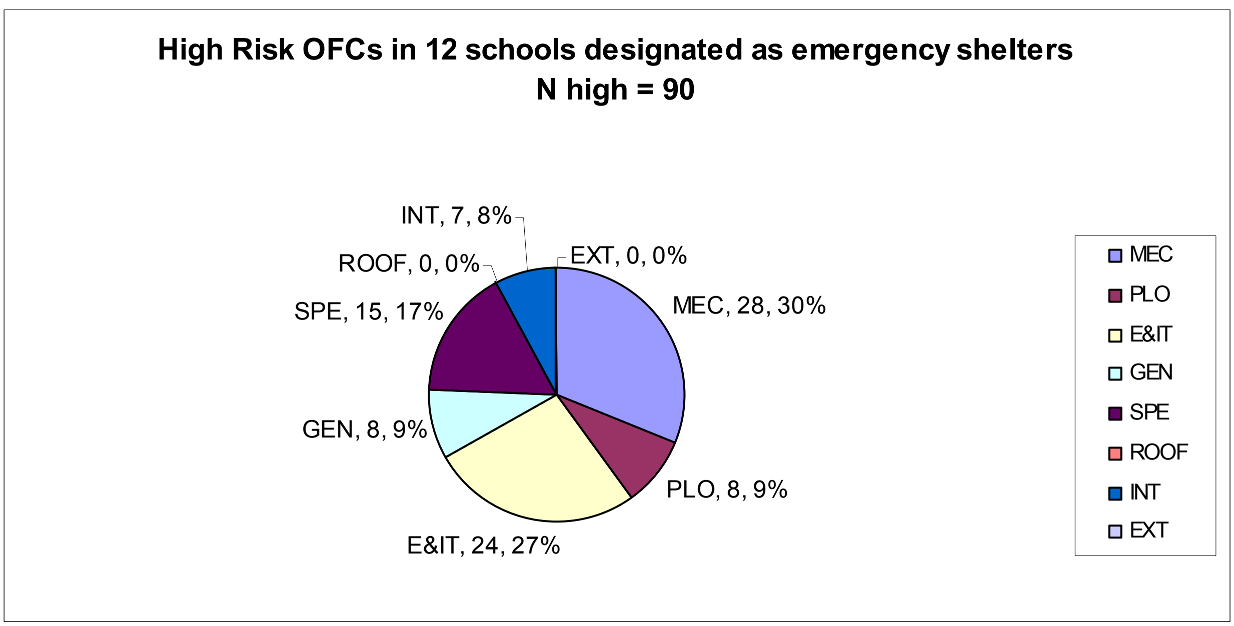

Figure 6. Detailed classification of the 90 high risk school components according to their specific function (Legend defined in caption of Fig. 3).

Another concern is that the capacity of the power generators installed in schools is generally insufficient to support the electric power demand of the emergency shelter occupancy. It is important to note that the main function of these generators is to provide electricity for emergency lighting and safe evacuation of a school building in case of a prolonged power outage.

When the school occupancy is considered, unrestrained suspended ceilings located in assembly areas pose an obvious safety threat to occupants during strong shaking and may block egress routes. Also, various unrestrained shelving systems located in laboratories and libraries present a high risk. Laboratories are questionable since many of the shelving cabinets have sliding glass panels. Furthermore, none of the libraries inspected had their bookshelves restrained; these components are slender, can easily overturn and trigger progressive collapse.

The retrofit indices, RI, for the high risk OFCs evaluated in schools range from 37% to 100%, and 66% of the components have a retrofit index above 60%. These results are similar to those found in hospitals, and indicate that individual mitigation of OFCs would be very beneficial to reduce their seismic risk.

10. Conclusion

The paper has summarized the results of a study of the post-earthquake functionality of six hospitals and a dozen schools designated as emergency shelters on the Island of Montréal. The risk rating procedure proposed in CAN/CSA S832-06 has been applied. The results indicate that 27% of the components inspected in hospitals and 20% of those inspected in schools receive a high risk rating, while the majority of the components have a moderate risk. The most common deficiency observed in high risk components is their lack of restraint to the supporting floor, which is relatively straightforward to mitigate. More evaluations are planned in community schools and other types of emergency shelters. The main goal remains to inform post-critical facilities stakeholders of the risks involved and the mitigation techniques available to improve the post-earthquake functionality of their installations.

Acknowledgments

This project was funded in part by NSERC through the Canadian Strategic Research Network on Reducing Urban Seismic Risk, and by the Faculty of Engineering of McGill University with funding for summer research assistants.

References

Canadian Standards Association (CSA), 2006. *Seismic Risk Reduction of Operational and Functional Components (OFCs) of Buildings, CAN/CSA-S832-06*. CSA, Rexdale, Ontario.

Foo, S., Ventura, C., and McClure, G., 2007. An overview of a new Canadian standard on the seismic risk reduction of operational and functional components of buildings. *Proceedings of the Ninth Canadian Conference on Earthquake Engineering*, 26-29 June 2007, Ottawa, Ontario, 292-302.

National Research Council of Canada (NRC), 1953, 1995 and 2005. *National Building Code of Canada*. National Research Council of Canada. Ottawa, Ontario.