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**Effect of critical sub-system failures on the post-earthquake functionality of
buildings: A case study for Montreal hospitals**

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ABSTRACT:

When an earthquake occurs, hospitals are expected to remain functional as they play a crucial role in emergency care operations. This ability to ensure the continuity of quality operations while ensuring the safety of occupants during and after an earthquake defines the concept of post-earthquake functionality. Hospital functionality relies on the good performance of a large number of critical sub-systems, components and equipment. Although the global seismic performance of building structures and their non-structural components was extensively observed in several post-disaster reconnaissance surveys, there is few and incomplete information on the effect of building and non-structural damage on post-earthquake functionality. The objective of this paper is to present a methodology for the assessment of post-earthquake functionality of existing Montreal hospitals using fault-tree analysis. The study shows that using specific and accurate information on the vulnerability and fragility of structural and critical non-structural components, a probabilistic index of post-earthquake functionality of the entire facility is computed which informs mitigation action for the critical failure processes through the system.

Keywords: Buildings; seismic evaluation; performance-based earthquake engineering; system reliability

1 INTRODUCTION

Nowadays, the seismic performance expected from a building structure is linked to its use and occupancy as well as to the social, economic and operational impacts resulting from a poor performance (Gupta and Krawinkler 1999). As such, even when structural damage is minimal, some buildings become dysfunctional following moderate earthquakes. This is referred to as domino effect, technological failure or more directly, loss of functionality.

Oddly enough considering the main goal of building codes, these concepts are relatively new in earthquake structural engineering. They are based on the analysis of the consequences of local failure of critical operational and functional components (OFCs) in the system. Experiences from large earthquakes such as in Northridge, California (January 17th, 1994 - M_w 6.7), Kobe, Japan (January 16th, 1995 - M_w 6.9), Kocaeli, Turkey (August 17th, 1999 - M_w 7.6) and Chi Chi, Taiwan, China (October 20th, 1999 - M_w 7.6), have highlighted the fact that the post-earthquake functionality of hospitals largely depends on the good performance of its non-structural components and equipment (Myrtle et al. 2005). In each of these disasters, and even in more recent events, health care facilities had to be evacuated (Davidovici 2007; EERI 2009, 2010; Myrtle et al. 2005; NCREE 2010).

These observations initiated new research towards the understanding and improvement of seismic behaviour of OFCs. These include seismic assessment and conducting experimental investigations of OFCs, the development of database and provisions or guidelines for seismic design and seismic risk reduction of OFCs (PWGSC 1995; Soong

et al. 1999; Chong and Soong 2000; Filiatrault et al. 2003; CSA 2014). From a post-earthquake functionality point of view, the focus has been made on a better understanding of damage propagation within a system and to improve codes and construction standards, especially in high seismic risk regions (Johnson et al. 1999; Myrtle et al. 2005; Nuti and Vanzi 1997; Porter et al. 2006; Scawthorn 2011; Shinozuka et al. 2004; Yavari et al. 2010).

In Eastern Canada, the Saguenay earthquake (1988, M_w 5.9) is one of the largest and most damaging event to have occurred in recent decades; damage reports on hospital buildings from this event are also the only ones documented in Canada, despite a higher seismic hazard on the West Coast (Hanna 1993). Although no severe structural damages (except to the Montreal East City Hall building that suffered foundation failure) or major fires were reported, this earthquake provided an excellent opportunity to investigate the “serviceability performance” of critical buildings in the event of stronger earthquakes (Mitchell et al. 1990). Observations from damage reconnaissance teams in hospital buildings highlighted the following: 1) the abundance of damaged unreinforced masonry (URM) walls poorly fastened to the structures, 2) the vulnerability of operational systems dedicated to essential services: communication and water pipes systems and the managing rescue and evacuation operation and 3) the presence of local site conditions that tended to amplify shaking levels and structural damage. According to the detailed analysis of building damage, 36 hospitals were affected at a distance up to 350 km from the epicenter (Paultre et al. 1993). Although most of the available damage data remains qualitative and limited, these observations highlight the vulnerability of existing buildings and indicate potential dysfunction of post-disaster buildings for moderate seismic events

due to damaged operational and functional components. As summarized in Table 1, small horizontal accelerations were recorded in Quebec city, but significant non-structural damage did occur in two hospitals built on soft soil (Mitchell et al. 1990).

Recent changes to the seismic provisions of the National Building Code of Canada (NBCC 2010) provide more explicit requirements in relation to the performance of post-disaster buildings (IRC-CNRC 2010). Immediate occupancy of these buildings is mandatory for rare earthquakes with a hazard level of 2% in 50 years. Therefore, it can be assumed that for more frequent events (10% in 50 years), the full functionality should be maintained. In both cases, the structure shall retain most of its initial strength and stiffness, while essential non-structural components and critical systems could suffer only minor or no damage. For non-structural components in existing and new buildings, the Canadian standard CSA-S832-14 (CSA 2014) complements the NBCC clauses that apply to new buildings only, and suggests a methodology for seismic risk assessment of individual OFCs. The OFC risk assessment procedure accounts for interdependencies between the building structure, the building content and its non-structural components and subsystems, and their interfaces with lifelines.

1.1 Evidence of interdependencies in hospitals

A hospital is a complex and highly interactive system of structural components, operational and functional equipment and personnel providing services. Figure 1 reflects this interactivity/interdependency in a post-earthquake functionality context. The overall reliability of the hospital system is determined by: 1) the seismic vulnerability assigned to each OFC; 2) the seismic vulnerability of the structure and its vertical and lateral load

resisting systems and; 3) the vulnerability of its various utility interfaces (electricity, water, gas, telecommunication, etc.), which are all directly influenced by seismic hazard and geotechnical site effects. The dashed line in the figure represents the interaction of seismic performance involving the building structure, the OFCs and their subsystems and the service lifelines and interfaces. The interaction between the different components is complex and the system functionality cannot be achieved by a simple sum of subsystem vulnerability or component indices.

1.2 Research Significance

The main objective of this study is to develop a methodology to assess the seismic risk of a health care centre (Montreal hospital), with the consideration of the interaction between various physical elements. The study describes the concept of system interaction in hospitals along with the Fault-Tree Analysis (FTA) method that is used to collect and analyse data. The effect of interactions between critical sub-systems on the post-earthquake functionality of the whole is illustrated by a case study of two essential hospital systems: Heating, ventilation and air conditioning (HVAC) and life support systems. The seismic risk for independent critical health care facilities is assessed through a post-earthquake functionality index giving valuable insights on salient risk contributors and eventual mitigation action.

2 RISK ANALYSIS FRAMEWORK FOR COMPLEX SYSTEMS

2.1 Methodology

To quantify the consequence of failure, the authors proposed an iterative approach: 1) a qualitative phase in order to conceptualize the hospital systems using fault tree model, and 2) a quantitative phase based on a combination of existing procedures and methods:

- The seismic vulnerability of the buildings is evaluated from the updated version of the NRC-92 procedure (Rainer et al. 92);
- The seismic risk associates to the OFCs is evaluated according to the CSA 2014 methodology (CSA 2014);
- The probability of damage to OFCs is estimated from fragility functions developed by HAZUS (NIBS 2013);
- The probability of failure within a system is computed using fault tree analysis (MIL-STD-1629A 1980; Vesely et al. 1981).

2.2 Infrastructure interactions and complexities

In a theory of “normal accidents”, Perrow (1984) suggested that systems of high complexity, coupling technology and organization are subjected to cascading failures. Considering the widespread presence of technology in society’s common operations and essential infrastructure, this notion has evolved and expanded to various fields such as economy or national security (Dhillon 1999). In this perspective, Rinaldi et al. (2001) proposed a conceptual framework for addressing infrastructure interactions and complexities in terms of six “dimensions”, to clarify the various aspects of interactions within complex systems (See Table 2). The interdependencies are defined by

bidirectional relations between infrastructures or as intrinsic relations within a given infrastructure. The problem of complex system analysis and infrastructure interactions can also be defined in the form of a set of questions as proposed by Limnios (1991). The proposed framework for the analysis of hospital's complex systems follows these concepts and identifies global objectives and models for risk analysis based on the fact that seismic performance of components depends on their vulnerability and fragility (Table 2).

To determine the reliability of the system, one needs to assess its failure scenarios and determine the influence of a given component state or a default type on the whole. The main challenge is then to conceptualize a functional hospital system that can accurately represent the component and sub-system interdependencies, the interface complexities, the component and sub-system failure modes and the associated losses or consequences. The proposed approach is to construct the functional hospital system using Fault Tree Analysis (FTA) that is commonly used in risk analysis of complex systems modelled by random variables (MIL-STD-1629A 1980; Vesely et al. 1981).

A fault tree is a logical graph representing the various combinations of basic failure/malfunction events susceptible to occur in a system. The fault tree depicts the relationship between the Output (higher event) and Input (lower event) as a Boolean gate (.AND. / .OR.) in order to evaluate the probability of failure of the higher event. When the first failure (lower event) occurs, an .AND. gate represents relationships between all the input faults in such way that the system will automatically rely on the next input event in the row to survive, whereas an .OR. gate indicates that the system will fail. The .AND.

gate therefore expresses a more robust and redundant system. This deductive analysis from the higher event will proceed until reaching all lower event or individual components or equipment failure modes. Moreover, FTA offers modularity and flexibility that enable specific accommodations to the required scenarios, such as change in the components or sub-systems interdependency or the possibility of using another probability theory.

2.3 Quantitative analysis methodology

Subsequent to the qualitative process of mapping the system FTA, a quantitative analysis can proceed by defining a Priority Risk Index (PRI) for each lower event. This is called Failure Modes, Effects & Criticality Analysis (FMECA), aiming to identify failures that have significant (or undesirable) effects on system performance. As expressed by Equation 1, PRI is the simple product of a risk level (SRI, Seismic risk index in the present application) and the probability (P) of reaching or exceeding a given damage level or failure. This application is more inherently simple than usual FMECA as the failures will all be initiated from damage due to an earthquake.

$$[1] \quad PRI = SRI \times P$$

The resulting PRI_i for each lower event i is then injected into the fault tree to obtain the final post-earthquake functionality index (PFI_j) of a system j by algebraic calculation rules. These rules highlight the weaknesses in systems as the fault tree represents all possible failure paths or direct effects of damage to components (Equations 2 and 3). The

proposed methodology allows to quantify the consequences of interdependent failures from individual component dysfunctions.

$$[2] \quad \text{.AND. gate : } PFI_j = PRI_1 \times PRI_2 \times \dots \times PRI_i$$

$$[3] \quad \text{.OR. gate : } PFI_j = 1 - (1 - PRI_1) \times (1 - PRI_2) \times \dots \times (1 - PRI_{i-1})$$

The PFI has an optimal value of zero, which corresponds to a system fully functional or in which the top event has an ideal zero probability of occurrence. For example, low PFIs typically indicate optimal base event conditions with a low probability of damage or high redundancy.

The implementation of this quantitative post-earthquake functionality analysis for Montreal hospital buildings relies on the construction of a reliable database on seismic vulnerability information to define the risk level, SRI. The probability of failure P of non-structural components could be obtained from fragility curves expressed in terms of spectral acceleration or spectral displacement, as appropriate to their failure modes.

3 OVERVIEW OF MONTREAL HOSPITALS AND SEISMIC VULNERABILITY CONTEXT

The portrait of Montreal hospitals shows a wide range of building types housing various critical services, local site conditions and seismic characteristics. In an Eastern North American context where observed earthquake damage data are scarce, those factors have to be combined to create damage models in the perspective of post-earthquake

functionality assessment. According to the last annual report of Montreal's Health and Social Services Agency, the Montreal Island population, estimated to 1.9 million, received health care services from 81 institutions and around 400 facilities and service points distributed throughout its 499 km² territory (ASSSM 2014). Among those institutions, 31 are categorized as hospitals, i.e. general and specialized or ultra-specialized care facilities offering emergency services, nursing, paediatric and mental health care and other services including medical imaging, nuclear medicine or rehabilitation services: these are mapped on Fig.2.

These hospitals are generally composed of several buildings that are structurally independent, i.e. separated by structural joints. In Montreal, half of them have been built between 1950 and 1970. They are pre-code in terms of seismic design according to NBCC. Typically they consist in large buildings of low to medium height (up to 14 stories) with few exceptions (see Fig. 2). The most common structural systems are steel braced frames, steel frames with masonry infills and reinforced concrete frames with masonry infills. Individual buildings are usually of rectangular footprint with few vertical or horizontal irregularities. Heavy load-bearing masonry walls are used in the oldest constructions, built before 1920 (22% of buildings): These buildings will be closed down and their services relocated in new buildings under construction. Two facilities, Montreal General Hospital (MGH) and Rivière-des-Prairies Hospital (RDPH), have been retained as case studies to develop a database on seismic vulnerability with three main damage factors: 1) seismic hazard (10% and 2% in 50 years occurrence), 2) site category (stiff to soft soil, site classes A to E according to NBCC), and 3) building fundamental period.

MGH is a designated Adult Trauma Centre and RDPH is specialized in Pediatric and Adolescent psychiatric care, therefore both hospitals bring specific challenges related to post-seismic functionality. Hospital building managers are aware of this complexity and have set up management systems to detect hazard, communicate alerts, and respond promptly and efficiently. Main critical OFC systems are designed to be redundant and secondary systems provide additional or more specific services. For example, hospitals typically use multiple sources of energy or connections to water or power supply utility network with backup systems for fast recovery in case of interface or external failure. Internally, there is redundancy in almost all of the essential OFCs such as power generators, boilers, filter systems, pumps for medical air production, etc. to ensure continuity of operations in case of a component dysfunction during normal building operations. Fault trees of the analyzed systems are developed in section 4.

With around one million square feet, the MGH operational area is about twice the RDPH's. As illustrated in Figure 3, both hospitals are comprised of several blocks, typically steel braced frames with uniform plan joining at right angles, simple façades and flat roofs. Diagonal bracings are located at the perimeter of each block and are made of symmetric steel plates and angles.

4 DEFINITION OF RISK LEVEL (SRI) FROM SEISMIC VULNERABILITY

DATA

As a first step, a qualitative risk assessment process, based on a visual in-situ inspection of ten MGH and RDPH buildings, has been conducted to collect information on structures and non-structural components being part of 17 critical systems. The structural

inspection followed the procedure for rapid visual screening of buildings described in NRC-92 and updated to the more recent seismic provisions of NBCC 2005 (Rainer et al. 1992, Saatcioglu et al. 2013). The non-structural inspection is carried out in accordance with the parametric procedure described in CSA-S832-14 *Seismic risk reduction of operational and functional components (OFCs) of buildings*” (CSA 2014). The results are expressed by a Seismic Risk Index (SRI) for each building and each OFC.

Collected data were used to generate samples of 76 cases for the structure and 4044 cases for the OFCs or 224 critical systems. The SRI serves to estimate the seismic vulnerability as function of each damage factor or in other words, is an indication of potential structural or non-structural damage that could hinder the global functionality of hospitals at the urban scale of Montreal Island. This database encompassed the SRI values obtained for the hospital buildings and OFCs that were inspected.

The two sets of data are statistically analysed to identify their main trends and define four levels of risk (slight to very high). The definition of risk levels harmonizes the overall methodology with the damage levels (from slight to complete) considered in fragility functions or probability of damage (P).

The risk levels and their relative threshold values for the SRI index proposed in Table 3, have been defined in accordance with CSA-S832-14 and expert judgement within the range of the calculated SRI values. The normalized rank highlights the high seismic vulnerability of the last two classes for which mitigation measures or further evaluation are mandatory.

SRI indices for the structure were generated from the parametric combinations that could trigger seismic deficiency, as follows: (i) three groups of buildings according to their fundamental period ($T \leq 0.2$ s; $0.2 \text{ s} < T \leq 0.5$ s; $T > 0.5$ s.); (ii) five seismic site classes, and; (iii) the presence of structural irregularities. The maximum SRI value generated is 63 and represents an irregular structure with a fundamental period of 0.5 s and located on a site class E (soft soil). The minimum SRI value of 3.0 was found to be larger than the threshold value for low risk ($\text{SRI} \leq 2$) as illustrated in Figure 4, a reflect of the age of the buildings used to build the database (pre-code buildings). The dashed line shows the threshold of moderate seismic risk level to the structure. The global distribution of SRI index confirms the importance of structural irregularities and site amplification effects on the seismic vulnerability.

The SRI for non-structural components is obtained for each OFC from the risk index (R) defined in CSA-S832-14 as the product of a vulnerability index score (V) and a consequences index score (C). SRI index values for OFCs were generated by varying the parameters of building characteristics, site categories and ground motion characteristics, for a total of 4044 cases. The statistical analysis of these results is summarized in Figure 5 with the dashed line showing the moderate risk level threshold ($\text{SRI}=64$). It is seen that the first two levels of risk (slight and moderate) are obtained in most cases (88% of the database), for either all site categories for a 10% in 50 years hazard or site A and B for a 2% in 50 years event. However, the limit of the high risk category was lowered to 86 instead of 128 as recommended by the standard CSA-S832-14, to highlight the very high risk associated with site category E (or upper 5% extreme values).

5 DEFINITION OF PROBABILITY OF DAMAGE (P) FROM FRAGILITY DATA ANALYSIS

Fragility curves refer to mathematical functions describing the probability of reaching or exceeding a given level of damage state (DS) related to a given level of ground shaking (or ground failure). Equation 4 assumes that seismic demand is represented by the spectral displacement S_d , a valid assumption for the building structure and displacement-sensitive OFCs:

$$[4] \quad P[DS | S_d] = \Phi \left[\frac{1}{\beta_{DS}} \ln \left(\frac{S_d}{\bar{S}_{d,DS}} \right) \right]$$

In this equation, $\bar{S}_{d,DS}$ is the median value of the spectral displacement for specified DS, β_{DS} , the standard deviation of the lognormal distribution and Φ represents the lognormal cumulative standard normal distribution. Discrete probabilities of damage are used directly as inputs to induced physical damage into systems of components and the structural system (NIBS 2003).

Extensive literature covers the development of those parameters from empirical, analytical or mixed approaches. Among them, the HAZUS methodology proposed fragility values for $\bar{S}_{d,DS}$ and β_{DS} for a large range of structural building types modelled as an equivalent single-degree-of-freedom model (ESDOF), acceleration-sensitive and displacement-sensitive non-structural components (NIBS 2003). HAZUS values are frequently used to define fragility curves when specific regional data are sparse, as is the case for Montreal. Although fragility data in HAZUS were developed for buildings in the

US, hospital building's structural types and occupancy class are compatible with the description given in HAZUS. At this stage of the research, the assumption that HAZUS's fragility data could be used in the context of Montreal is considered reasonable. However, authors are aware of this limitation which highlights the need for research and development of specific fragility data for the Canadian context.

For both structural and non-structural components, fragility values are given in terms of equivalent peak ground acceleration (PGA) or spectral seismic demand (pseudo-acceleration S_a or spectral displacement S_d), depending on the damage mode of the component. This approach is therefore well suited to quantify the post-earthquake functionality of few specific buildings and a large number of non-structural components. However, a drawback of using HAZUS fragility values is that the probability of damage for non-structural components is only defined in terms of total drift of the building (Eq. 4), which is not a correct indicator for components that are sensitive to inter-story drift or accelerations, or both. More specific fragility information should then be used to better reflect this type of vulnerability.

The model parameters used to build the ESDOF model of the studied buildings are extracted from ambient vibration measurements, and period values were found to vary from 0.16 s to 1.2 s. Seismic demand indicators at an equivalent height, S_a and S_d , are computed directly from the Uniform Hazard Spectra for Montreal and for both 2% and 10% in 50 years occurrence. Figures 6 and 7 provide the fragility curves obtained for both drift and acceleration sensitive OFCs and for four damage states: slight, moderate, extensive and complete. A similar procedure has been followed for the structure seismic fragility. Values (median and deviation) from HAZUS take into account: 1) seismic

design level (Low level), 2) building type (Steel moment frame S1), 3) building height (Low, Medium, High), 4) facility classification (Essential facilities) and 5) sensitivity (NIBS 2003). It should be noted that for acceleration-sensitive OFCs, there is no significant variation in the fragility with the height of the structure (see Figure 7).

As mentioned previously, one specific seismic demand (OFC or building) is related with four values of P (Figure 7), which will be reflected in the distribution of system PFI indices. The levels of risk for structural and non-structural SRI defined in the previous section, as well as the fragility information will be used in the following section to illustrate the application of the proposed methodology to calculate a PFI index for critical systems using fault-tree analysis.

6 CASE STUDY

This section presents an overview of the reliability analysis of two critical functional systems: 1) HVAC (Heating, ventilating, and air conditioning) and 2) life support including medical gases production, as built at the Montreal General Hospital. The PFI is obtained for a structure having a fundamental period of 0.5 s, a slight probability of damage, and a seismic hazard level of 2% in 50 years occurrence. The risk index (PRI) - Equation 1, is computed for each component at the base of the fault tree (event, EVi) considering different seismic hazard and site conditions. The upward computation of PFI is then carried out using Boolean algebra equations 2 and 3, as illustrated on the system fault trees of Figures 8, 9 and 11 built with Isograph (Isograph Ltd. 2011). In order to have the complete PFI index distribution for this building, the same procedure has to be applied to the other damage levels (moderate, extensive and complete).

6.1 HVAC system

HVAC systems in hospitals are required to achieve a variety of critical functions with high levels of performance. Examples of such functions include maintaining optimal levels of air quality, humidity and heat to ensure infection control; special care is needed for hazardous substances used in medical treatments, which require air exchange, treatment and complex filtering. HVAC systems are also key to fire detection and space pressurization with exhaust devices.

Montreal hospital HVAC systems typically include a central heating system and air conditioning systems and ventilation units according to serviced areas (corridors, operating room, emergency, magnetic resonance, critical areas, etc.). Moreover, given the importance of the good performance of the HVAC system to maintain continuous hospital functionality, it is also connected to emergency power supply sources. The HVAC system fault-tree includes the following sub-systems (cf. Figure 8):

- The central heating system including OFC unit that is necessary for the production of heat or steam supplemented in some cases by storage tanks and hot water reservoirs for domestic needs (sterilization and humidification). The fault tree identifies two main sub-systems: *sub-system 1* - heat and steam production system (Gate 1, GT1), and *sub-system 2* – hot water production (Gate 2, GT2). Under each gate a lower event (EV1 to EV11) identifies a specific OFC unit.
- The interface system to buildings could be represented by supply pipes (drinkable water pipes, shut-off valves or check valves, etc.) connected to the main municipal water supply network. Seismic requirements for shut-off valves or check valves for supply pipes vary, somehow, from a region to another (FEMA

2011). Seismic design guidelines for these components, and in particular for supply pipes containing hazardous materials, lack a strong rational basis due to the scarcity of research data, as indicated in CSA-S832-14.

- HVAC systems use air conditioning to remove heat from one area and ventilation to maintain a comfortable environment usually through cooling towers and air-cooled condensers using a refrigerant (mainly glycol) and evaporative condensers in some cases integrate with a cooler (see Figure 9). The fault tree of a typical air conditioning system identifies the top event (TP1) as depending of two main sub-systems: 1) the chiller system (Gate 1, GT1), 2) the air treatment system (Gate 2, GT2), 3) the distribution system (Gate 3, GT3), and 4) the water pipe system (EV1). Under each gate, a lower event (EV2 to EV9) identifies a specific OFC unit such as chillers, filters, redundant power source, control equipment and piping systems. The complexity of the control system depends on the sophistication of the many subsystems to be monitored. Figure 10 shows examples for domestic water supply and air filter systems.

6.2 Life support system

Figure 11 shows the fault tree of a life support system including systems for in-situ production of medical gases (GT1), physiotherapy, intensive care and decontamination equipment (GT2 to GT4). The main distribution network for medical gas is composed of a set of three sub-systems (including pipe systems) and their control: 1) centrifugal compressor for medical air production (GT5), 2) vacuum pumps for suction gas production (GT6), and 3) high pressure portable cylinders (EV1). At the end of the distribution network or in medical care areas, power modules for medical gases must pass

stress tests to dynamic and static forces as required by standards; they are not considered in this analysis.

Single OFCs in subsystems GT2 to GT4 are mainly mobile devices (gas cylinders) that could pose life safety issues as they can be stored with inadequate restraints. All OFCs at the base are considered acceleration-sensitive (Figure 7).

7 DEAGGREGATED VALUES OF POST-EARTHQUAKE INDEX

7.1 Extended PFI values at urban Montreal scale

Figures 12 to 14 present PFI values obtained for the four levels of damage considered (slight, moderate, extensive and complete) as function of : (i) seismic hazard (10% and 2% in 50 years occurrence); (ii) site category (stiff to soft soil, A to E), and; (iii) building fundamental period T . These figures illustrate the PFI distribution for different buildings and cumulative damage level, for rapid identification of conditions that hinder hospital functionality. From this deaggregation analysis, the following observations can be made:

- As expected, structural PFI is directly proportional to the vulnerability of the building and the probability of damage ($PFI = PRI$), and structures on soft soils are the most affected. But while no structural PFI reveals significant risk of complete damage (Figure 12), OFC systems can experience damage from slight to complete. This emphasizes the importance of insuring OFC functionality even for low seismic hazard. Figure 12 is scaled at 1/10 compared to Figures 13 and 14 related to PFI for OFC.
- For both structural and non-structural systems, PFI values show peaks for buildings on sites C to E; particularly in taller buildings with fundamental period

higher than 1 s. Mitigation measures are therefore mandatory for these high PFI values.

- Exclusively comprised of acceleration-sensitive components, the analysis indicates that the life support system has the highest PFI. In case of a 2% in 50 years earthquake and a low-rise building (itself sensitive to acceleration), the life support system could present failure for all sites (see figure 14). However, in a more specific study, PFI values shall be less since acceleration at equivalent roof level is used in the generic evaluation.
- The proposed methodology can be used in a screening process as the dysfunction depends jointly on the likely occurrence of an earthquake, the inherent structural vulnerability and the fragility states considered.

7.2 Interpretation criteria

The probability of damage P (from slight to complete damage) alongside the risk levels SRI (from slight to very high) are grouped into a risk matrix to develop PFI interpretation criteria (Figure 15). It is seen that to achieve hospital required levels of performance; the only acceptable combination is slight damage with slight risk. Obviously, unacceptable performance will occur when considering a probability of complete damage and a very high seismic risk. The matrix form facilitates risk interpretation to support decision making for mitigation action.

More specifically, the performance of the studied systems can be interpreted and as follows:

- For the HVAC system exposed to a seismic hazard of 2% in 50 years, 95% of

OFCs have a moderate risk when on site Class A, whereas 75% of OFCs are at very high risk when on site Class E. The expected performance levels are, respectively, immediate occupancy and unacceptable performance. For a hazard level of 10% in 50 years, the PFI values are all less than 0.4 and the PRI indices are concentrated in areas of low or moderate damage, suggesting an acceptable level of performance of either complete functionality or immediate occupancy;

- The life support system shows a uniform distribution of high PFIs (close to one) for a seismic hazard of 2% in 50 years. This could be attributed to the fact that unrestrained portable components reach high or very high risk level index (SRI). Post-earthquake functionality will be highly hindered with life safety challenges posed by such components.
- Finally, the expected performance of critical systems in hospital buildings on Montreal sites of class D or E will be minimally in the life safety range for a seismic hazard of 2% in 50 years.

8 CONCLUSIONS

The predictive approach for the assessment of post-earthquake functionality of hospital systems mainly focuses on modelling and on risk assessment of non-structural components. To illustrate the approach and assess how component failures propagate through a system, two case studies of OFC systems were analysed and discussed. According to the proposed methodology, the risk level is considered in a unified way for all types of non-structural components and the structure, through indices obtained from the application of known and largely used seismic evaluation procedures as well as fragility information. The final post-functionality index (PFI) resulting from the

procedure takes into consideration interdependencies within the systems and with the structure, as reflected in fault trees. Data collection on specific components (4044 OFCs) and buildings (76 units) reduced the uncertainties associated with the computation of the PFI index. It appears that the proposed methodology gives an accurate picture of the earthquake survivability of Montreal hospitals and consequently can inform decisions pertaining to mitigation. However, further research is needed to improve the information on the probability of damage to operational and functional components of buildings.

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NOTATION

DS: Damage state

IS: Structural index according to NRC-92

PFI : Post-earthquake functionality index

PRI : Priority risk index

SRI : Seismic risk index

P : Probability of damage value

V, and C: Vulnerability and Consequence indices according to CSA 2014

S_a : Spectral acceleration

S_d : Spectral displacement

$S_{d,DS}$: Median value of the spectral displacement

T_a : Fundamental period

β_{DS} : Standard deviation of the lognormal distribution

ϕ : Lognormal cumulative standard normal distribution

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Table 1. Damages to hospital buildings during the Saguenay earthquake

Adapted from (Mitchell et al. 1990); Paultre et al. (1993)

Distance from epicentre and accelerations	Observed damages in hospital buildings
Epicentral region ($H_g = 0,156g$ $V_g = 0,102g$)	Minor architectural damages
150 km from epicentre ($H_g=0,05g$)	Significant non-structural damage to two hospitals in Quebec City due to amplification by alluvial deposits - Major cracking to exterior unreinforced masonry walls parallel to the weaker direction of the building - Collapse of two masonry chimneys - Cracked plaster in lift shafts and corridors - Derailment of an elevator shaft (lack of rigidity of the rails) - Shear failure in the concrete beam supporting the rails of a lift (when restarting the elevator) - Shear failure in MNA walls between the openings - Failure of the heating system radiator - Power outage for two hours (dysfunction of the emergency generator)

Table 2. Analysis framework for hospital systems
Adapted from Rinaldi et al. (2001) et Limnios (1991)

(Limnios 1991)	(Rinaldi et al. 2001)		Proposed framework	
Problem	Dimensions	Elements of interdependencies	Global objectives	Models
What are the failure modes of system components?	Type of failure	Common cause, cascading	Analyze the nature of the disturbance and the vulnerability and fragility of system components	In situ conditions or seismic vulnerability and Probabilistic model or fragility functions
	State of operation	Normal, repair/restoration, stressed/disrupted		
How does the system fail?	Types of interdependencies	Geographic, logical, cyber, physical	Define interdependencies between systems and degree of coupling	Algebraic model: Boolean operators .AND., .OR. (Fault tree analysis)
	Coupling and response behavior	Adaptive, inflexible, loose/tight, linear/complex		
How likely the system would be dysfunctional?	Environment	Social/political, technical, legal/regulatory, economic, health/safety, public/policy, business	Identify the infrastructure (or system) and its exposure to danger.	System representation models (FTA)
	Infrastructure characteristics	Organisational, operational, temporal, spatial		

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Table 3. Risk level definitions

Level of risk	Normalized rank	Structural SRI		OFC SRI	
		Threshold	Reference for risk level threshold	Threshold	Reference for risk level threshold
Slight	0.1	$SRI \leq 2$	(LeBoeuf and Nollet 2006)	$SRI \leq 16$	CSA-S832-14
Moderate	0.3	$2 < SRI \leq 10$		$16 < SRI \leq 64$	
High	0.5	$10 < SRI \leq 20$	Range for structures with any geometric irregularities except site E	$64 < SRI \leq 86$	Observations that are not outliers (upper whisker or 95 th percentile)
Very high	1.0	$SRI > 20$	Small buildings with irregularities (all sites) All buildings Sites D and E	$SRI > 86$	Extreme values (outliers) corresponding to range for Sites D and E

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