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ASSESSMENT OF POST-EARTHQUAKE FUNCTIONALITY OF ACCELERATION-SENSITIVE SYSTEMS IN HOSPITALS

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Abstract: As critical infrastructure, hospitals are key components for post-earthquake emergency response and need to be functional immediately after an earthquake. Their functionality is highly correlated to the performance of their acceleration-sensitive operational and functional systems such as the mechanical and electrical systems for medical air, fire protection, telecommunications and IT services, heating-ventilation-air conditioning (HVAC) and water distribution. These systems are susceptible to damage from amplified earthquake-induced floor accelerations. Their malfunction typically results in the disruption of the normal operation of the hospital, which can lead to evacuation even without significant damage to the building structural system. A quantitative evaluation of the post-earthquake functionality based on the concept of fragility functions of these systems is essential to inform decisions related to mitigation and emergency response planning. A fragility function represents a relationship between a seismic intensity measure (e.g. peak ground acceleration) and the probability of non-functionality of the system. This paper presents a methodology for the development of fragility functions for functionality assessment of acceleration-sensitive systems in hospitals. For a specific system (e.g. fire protection), the system-level fragility function is developed based on a fault-tree analysis of the probability of failure of acceleration-sensitive components (e.g. pumps, pipes, sprinklers) in order to estimate the probability of the system non-functionality (e.g. probability that the fire protection system is non-functional given a specific seismic intensity). In this context, peak floor acceleration is used as the demand parameter for the estimation of failure probability of the system components. The methodology is demonstrated by an example of development of a fire-protection system fragility function for a seven-story hospital located in Montreal, Quebec.

1 INTRODUCTION

As critical infrastructure, hospitals are key components for post-earthquake emergency response and need to be functional immediately after an earthquake. Hospitals comprise operational and functional systems that are either acceleration-sensitive systems or displacement-sensitive systems, or both. An operational and functional system is considered acceleration-sensitive if the inertia forces due to amplified floor accelerations govern its seismic design. Likewise, an operational and functional system is considered displacement-sensitive or drift-sensitive if its seismic design is governed by building displacements or inter-story drift limits. Many systems including their connections to the building structure can in fact be composed of both force- and displacement-sensitive individual components. Examples of dominantly acceleration-sensitive systems are the mechanical and electrical systems for medical air, fire protection, heating-ventilation-air conditioning (HVAC) and water distribution. Experiences from large earthquakes such as in Northridge, California (January 17th, 1994 - Mw 6.7), Kobe, Japan (January 16th, 1995- Mw 6.9), Kocaeli, Turkey (August 17th, 1999 - Mw7.6) and Chi Chi, Taiwan (October 20th, 1999 - Mw7.6), have highlighted that the post-earthquake functionality of hospitals largely depends on the performance of their acceleration-sensitive operational and functional systems. During these events, some hospitals had to be evacuated (a costly and complex operation) although their building structure remained almost intact with only minor, non-threatening structural damage (EERI 2009, 2010, Myrtle et al. 2005, NCREE 2010). These references have also highlighted that damage from water leakage from the fire protection systems is a common cause of malfunction in hospitals following earthquakes. Fire caused by the malfunction of electrical systems, explosions, etc., is a common consequence of earthquakes (Botting and Buchanan 2000) and represents a serious problem given the fire propagation potential and the limited response capacity in a post-disaster context. This highlights the importance of protecting the functionality of fire protection systems. Failure of fire protection systems, causes and consequences are well documented (Botting and Buchanan 2000; Schultz et al. 2003; Scawthorn et al. 2005; Mousavi, Bagchi et al. 2008, Tian et al. 2013; Youance et al. 2016).

A quantitative evaluation of the post-earthquake functionality of acceleration-sensitive systems based on the concept of fragility functions is essential to inform decisions related to mitigation and emergency response planning (Porter et al. 1993; Filiatrault et al. 2003; FEMA 2012a; Filiatrault and Sullivan 2014). A fragility function represents a relationship between a seismic intensity measure (e.g. peak ground acceleration) and the probability of non-functionality of the system (Porter et al. 2006). This paper presents a methodology for the development of fragility functions for functionality assessment of acceleration-sensitive systems in hospitals in order to determine the consequences as the building is subjected to seismic ground shaking.

For a specific system (e.g. fire protection), the system-level fragility function is developed based on a fault-tree analysis of the probability of failure of acceleration-sensitive components (e.g. pumps, pipes, sprinklers) in order to estimate the probability that the fire protection system is non-functional given a specific seismic intensity (Porter et al. 1993; Shinozuka et al. 2000; Youance et al. 2016). Peak floor acceleration is used as the demand parameter for the estimation of failure probability of the acceleration-sensitive system components. Note that in this case, all the components of the fire protection system are acceleration sensitive. The methodology is demonstrated by an example case study of functionality assessment of fire-protection system for a seven-story hospital located in Montreal, Quebec.

2 FUNCTIONALITY ASSESSMENT METHODOLOGY

This section presents the methodology for the development of fragility functions for functionality assessment of acceleration-sensitive systems in hospitals. The purpose of the functionality assessment is to relate shaking intensity to its consequences for a specific facility. In the present case, the consequence of interest is the probability that a specific acceleration-sensitive system is non-functional due to damage to its components from amplified earthquake-induced floor accelerations. In order to develop the functionality fragility functions for a specific system, the methodology proceeds in three sequential steps: (1) seismic hazard analysis; (2) seismic demand analysis; (3) fault-tree analysis. Fault-tree analysis is used to calculate the probability of non-functionality of the system’s components and as a result the probability of non-functionality of the system. The process is repeated at increasing levels of seismic intensity to develop the system fragility function.

2.1 Seismic hazard analysis

The seismic hazard analysis is conducted to identify the seismic input in terms of a seismic intensity measure IM at the hospital location. In this study, the IM is the peak ground acceleration, PGA, and is evaluated based on the 2015 edition of the National Building Code of Canada (NBCC) seismic hazard assessment corresponding to several selected probabilities of exceedance in 50 years (e.g. 40%, 10%, 5% and 2%) (NRCC, 2015).

2.2 Seismic demand analysis

The seismic demand analysis is conducted to correlate the IM to an engineering demand parameter (EDP) that better correlates damage to acceleration-sensitive components. In this case, the EDP is the peak floor acceleration (PFA) at the component location in the building. The FEMA-P58 (FEMA, 2012) simplified method for seismic demand analysis is used to predict the PFA corresponding to increasing levels of IM. At the base of the building, PFA is taken as equal to the PGA. At other floor levels, i, the estimate median PFA_i is derived from the PGA using Equations 1 and 2.

$$[1] \quad PFA_i = H_{ai}(S, T, h_i, H).PGA$$

$$[2] \quad \ln(H_{ai}) = a_0 + a_1\,T + \ a_2\,S + a_3\left(\frac{h_i}{H}\right) + a_4\left(\frac{h_i}{H}\right)^2 + \ a_5\left(\frac{h_i}{H}\right)^3$$

H_{ai} is the acceleration amplification factor. S is the strength ratio (the elastic spectral acceleration over the yield acceleration of the building) and is taken as 1.0 for elastic building response; T is the fundamental period of the building; h_i is the height above ground at which the component is located, and H is the total building height; the values of the coefficients a_0 through a_5 are obtained from Table 5-4 in FEMA-P58 for buildings having up to nine stories, and from Table 5-5 for buildings having 10 to 15 stories. The coefficients depend on the type of lateral load system (e.g. moment frames, braced frames, shear walls).The National Building Code of Canada (NRCC, 2015) provides an equation for the prediction of the acceleration amplification factor (called the height factor [$A_i = 1 + 2(h_i/H)$] compared to the ground acceleration. However, the limitation of the NRCC equation is the assumption of constant amplification factor (e.g. the amplification factor A at the roof level is 3) regardless of the type of the lateral load system, the fundamental period or the nonlinear response of the building.

2.3 Fault-tree analysis

Fault-tree analysis is used to calculate the probability of non-functionality of the system (Porter et al. 2006). A fault-tree is a diagram that shows, at its top, a box representing an undesirable outcome, such as “non-functional system” (See Figure 1). The possible causes of the top event are depicted below in a row of events that could cause the top event, such as a sub-system or component failure. These lower-tier events are connected to the top-tier event by lines and a logic symbol that indicates whether any of the lower events causes the top event (an “.OR.” gate, i.e., the top event occurs if the first or the second or the third or any combination of the lower events occurs) or whether all of the lower events must occur to cause the top event (an “.AND.” gate). Each lower event can be further broken down into even-lower events connected to the upper ones by logic gates, until the probability of all the lowest events (called basic events) can be estimated. Here, the basic events for an acceleration-sensitive system (e.g. fire-protection system) are the failure of its components (e.g. pumps, pipes, sprinklers). The probabilities of the basic events are estimated as a function of ground shaking intensity.

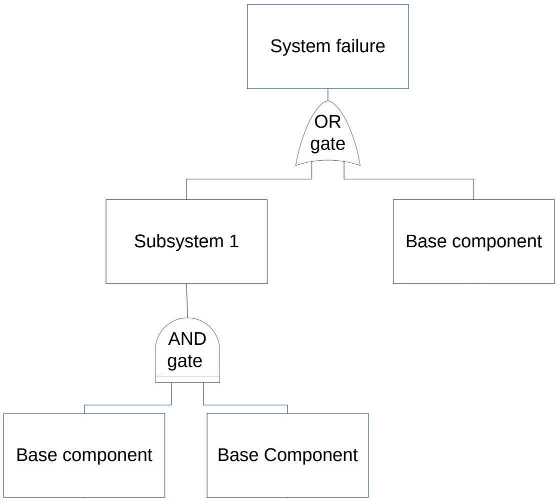

Figure 1. Illustration of a fault tree analysis.

The relationship between ground shaking intensity and failure probability of a component is here referred to as a component fragility function. The component fragility function depends on what kind of component is shaken and its installation conditions. To analyze the fault tree, one defines a mathematical equation expressing the probability of the top-tier event as a function of the probabilities of the basic events. The probability that event i occurs (denoted by Pi) if lower events 0, 1, 2, … and i-1 all occur is the product of the probabilities of the lower events (denoted by P_0, P_1 etc. in Equation 3). Finally, the probability that event i occurs if any one of the lower events occurs is given by Equation 4. Since the probabilities of the basic events are themselves functions of shaking intensity (e.g., the PFA of an equipment or component), one can calculate the probability of the top event as a function of shaking intensity, creating system fragility function for the top event. The system fragility function is then developed in terms of the probability of failure as a function of the base motion (PGA).

[3] $AND\ gate{:}\ P_i = P_0 \times P_1 \times P_2 \times P_{i-1}$

[4] $OR\ gate{:}\ P_i = 1 - (1 - P_0) \times (1 - P_1) \times (1 - P_2) \times (1 - P_{i-1})$

3 CASE STUDY

This section presents an application of the methodology used to develop fragility functions for acceleration-sensitive systems in hospitals. The selected case study hospital is the Montreal General Hospital (MGH) constructed in 1954. It is a Level-1 adult trauma centre in downtown Montreal. Such designation identifies a regional resource to the trauma system providing care from prevention to rehabilitation through diagnosis, treatment, research and teaching (CUSM 2017). The facility main building has a horizontal plane in H (see Figure 2), and is located on solid rock (seismic site class A according to NBCC (NRCC, 2015). The wings are structurally independent units and provide mainly care with essential services positioned at different levels indifferent buildings. These include the emergency department at the southern entrance of the hospital in wing A, surgery in wing C, and intensive care in wing E. The analyzed fire-protection system is located in wing A, a 9-story building with lateral load resisting system consisting of steel frames in the longitudinal and transverse directions.

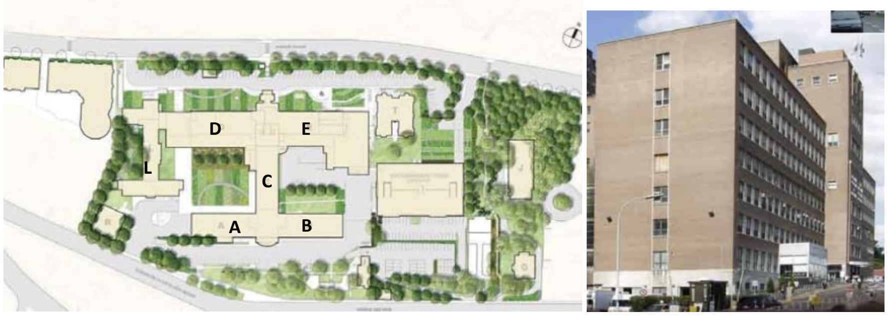

Figure 2. Layout of the Montreal General Hospital (L: campus; R: Wing A under study), (CUSM 2017).

3.1 Building system characteristics

Ambient vibration testing (AVT) of MGH buildings was carried out between 2010 and 2012 as part of a project aimed to develop a post-earthquake functionality index for the hospital (Youance 2015). AVT is now widely used for building system identification of modal parameters. The fundamental period of wing A was found equal to 0.6s. Since the majority of the acceleration-sensitive components are distributed along the height of the building, the average peak floor acceleration (PFA) along the height was considered as an input for the components fragility functions. Equations 1 and 2 are used to estimate the PFA at each floor levels from PGA values for seismic hazard analysis in Montreal for multiple probabilities of exceedance in 50 years. Then the average PFA along the height is estimated for each probability of exceedance (Error! Reference source not found.).

Table 1. The average PFA along the height of the building corresponding to multiple probabilities of exceedance in 50 years

Parameters	2% in 50 years	5% in 50 years	10% in 50 years	40% in 50 years
PGA (g)	0.38	0.22	0.13	0.04
Average PFA (g)	0.57	0.33	0.20	0.06

3.2 Fire protection system characteristics

With its role as a reference trauma hospital services on the Island of Montreal, the MGH presents many challenges in terms of post-seismic functionality. Hospital managers are well aware of this complexity and have implemented redundant systems and efficient detection and warning procedures to trigger prompt and adequate responses. To achieve multiple safety objectives, such as safe egress, life safety or to limit spread of fire, a standard fire protection system is comprised of the following subsystems or components: evacuators, stair pressurization system, fire doors, pre-action system (pressurized piping), wall phone, fire extinguishers, city water intakes (located in wing A) as well as a central reservoir and electric system. Possible earthquake damage of the fire protection system would mainly affect the sprinkler system. Large amounts of water released by rupture of pipes or sprinkler heads (permanently pressurized with water) have caused direct damage to hospitals in California, such as the evacuation of the Olive View Hospital during the Northridge earthquake in 1994 (Schultz et al. 2003). The fire protection system fault tree of the MGH consists of two subsystems: 1) detection and alarm, 2) response system (sprinklers, portable fire extinguishers generally redundant, fire pumps, etc.). The functionality of the hospital is ensured by the mitigation of water damage that is considered as the first level of damage (Figure 3).

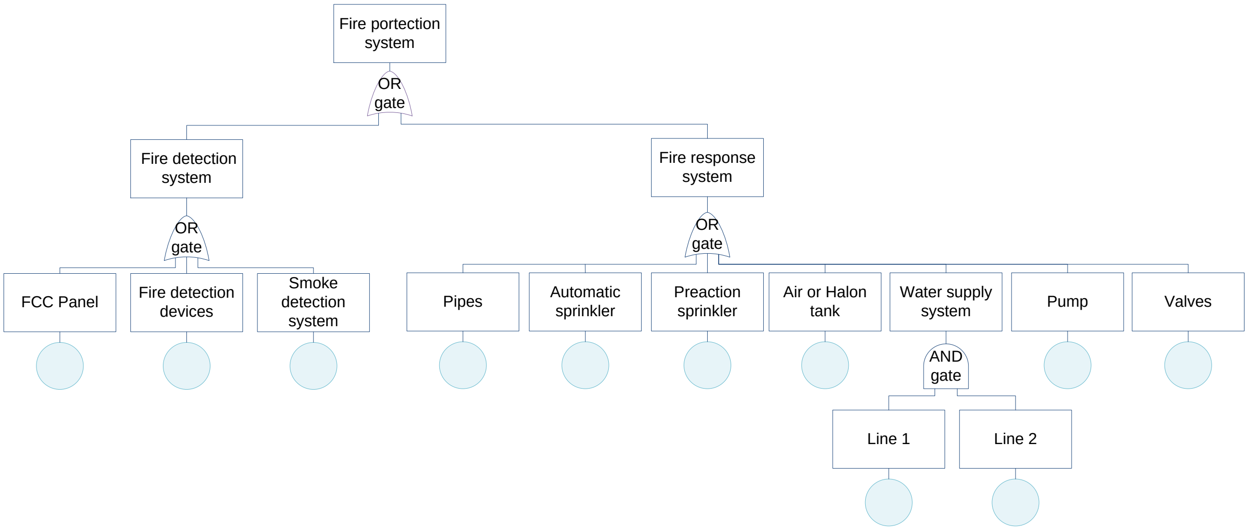

Figure 3. Fault tree for the calculation of the probability of non-functionality of the MGH fire protection system.

3.3 System fragility analysis

As an application of the method and to illustrate the procedure, the fragility function parameters were selected from the literature with the median PFA and the log normal standard deviation and are listed in Table 2. The tabulated parameters were mainly evaluated based on post-earthquake damage survey following major earthquakes in the USA (Porter and Ramer 2012). These fragility functions reflect the uncertainty in the resistance of each component in terms of threshold PFA that would cause the failure of the component. Using the fault tree analysis presented in Figure 3, the fragility functions of the fire protection system components are used to calculate the probability that the fire protection system is non-functional given a specific seismic intensity (in this case the PGA corresponding to multiple seismic hazard levels). The probability of failure of a component for a given PFA is calculated using Equation 5.

$$[5]\ P[Failure\ |PFA] = \Phi\left[\frac{1}{\beta_{PFA}} ln\left(\frac{PFA}{PFA_{med.}}\right)\right]$$

$PFA_{med.}$ is the median PFA threshold that causes damage to the component and the β_{PFA} is the log normal standard deviation of the component fragility function (Table 2). Table 3 illustrates an example calculation of the probability of failure of each component in the fire response subsystem corresponding to PFA=0.57g. Equations 3 and 4 are then used to combine the computed probability of failure to evaluate the subsystem failure probability (failure is represented here by the non-functionality of the subsystem). The probability equations are solved using Microsoft EXCEL. The calculations are repeated for different levels of seismic demand (see Table 1) to calculate the system fragility function for a range of accelerations.

Table 2. The acceleration-sensitive component fragility function parameters

	Acceleration-sensitive component	Fragility parameters		
		Median PFA (g)	Lognormal standard deviation	References
Fire detection system	FCC panel	4	0.4	(Porter and Ramer 2012)
	Fire detection devices	Redundant	n/a	n/a
	Smoke detection devices	Redundant	n/a	n/a
Fire response system	Pipes	1.9	0.4	(Porter and Ramer 2012)
	Fire extinguisher	Redundant	n/a	n/a
	Automatic sprinkler	1.3	0.4	(Porter and Ramer 2012)
	Preaction sprinklers	1.3	0.5	
	Air or Halon tank	1.9	0.5	
	Water supply Line 1	0.5	0.5	
	Water supply Line 2	0.5	0.5	
	Pump	2.6	0.5	(Eidinger 2009)
	Valve	4.5	0.5	

Table 3. Example calculation of the fire response subsystem failure probability at average PFA=0.57g

	Component	Median PFA (g)	Lognormal standard deviation	Probability (Equation 5)	Probability (Fault-tree analysis)	
Fire response subsystem	Pipes	1.9	0.4	0.001	0.07 (Equation 4)	0.41 (Equation 4)
	Automatic sprinkler	1.3	0.4	0.020		
	Preaction sprinklers	1.3	0.5	0.050		
	Air or Halon tank	1.9	0.5	0.008		
	Water supply Line 1	0.5	0.5	0.603	0.36 (Equation 3)	
	Water supply Line 1	0.5	0.5	0.603		
	Pump	2.6	0.5	0.001	0.001 (Equation 4)	
	Valve	4.5	0.5	0.000		

Figure 4 shows the system fragility function of the fire-protection system non-functionality as a function of the seismic intensity measure PGA. For the design level seismic hazard corresponding to 2% in 50 years, the PGA is equal to 0.38g and there is a 41% probability that the fire-protection system would be non-functional. Based on the fault-tree analysis results, the main contribution to the fire-protection system non-functionality at that seismic hazard level comes from the water supply fragility, which is characterized by the lowest median threshold acceleration (0.5g as shown in Table 2). The reader should note that the system fragility function in Figure 4 represents a first-order approximation since it is based on input parameters for the component fragilities from literature resources that might not necessarily reflect the actual installation at the MGH hospital. Calibration of the component fragility functions with site-specific installation conditions and with consideration of the uncertainties is the objective of current research by the authors. The results are presented to show the importance of the selection of components fragility on the failure probability of the system and the need for site-specific information for reliable evaluation of the post-earthquake functionality of hospitals.

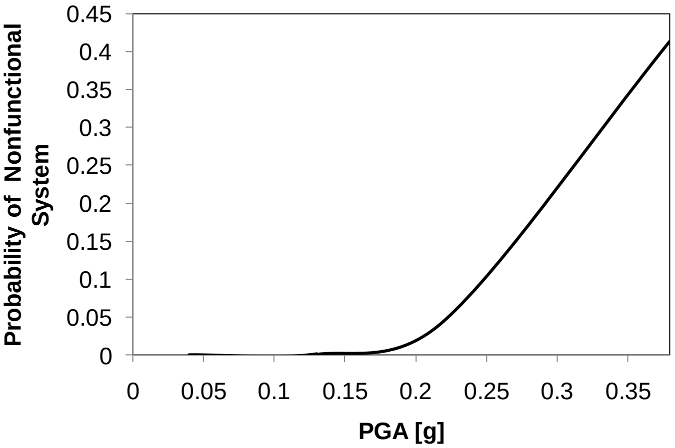

Figure 4. The MGH fire-protection system fragility function

4 CONCLUSIONS

Hospitals are key components for post-earthquake emergency response and need to be functional immediately after an earthquake. Their functionality is highly correlated to the performance of their acceleration-sensitive operational and functional systems that are susceptible to damage from amplified seismic floor accelerations. The non-functionality of these systems typically results in the disruption of the normal operation of the hospital, which can lead to evacuation even without significant damage to the building structural system. This paper presented a methodology for the development of fragility functions for functionality assessment of acceleration-sensitive systems in hospitals. For a specific system, the system-level fragility function is developed based on a fault-tree analysis of the probability of failure of system components in order to estimate the probability of the system non-functionality (e.g. probability that the fire protection system is non-functional given a specific seismic intensity). Peak floor acceleration is used as the demand parameter for the estimation of failure probability of the system components. The methodology was demonstrated by an example application to develop a fire-protection system fragility function for a seven-story hospital in Montreal, Quebec. As a first-order application of the method and to illustrate the procedure, the acceleration-sensitive component fragility function parameters were selected from the literature with the median peak floor acceleration (PFA) and log normal standard deviation. The methodology is particularly useful for hospital managers in making better informed decisions to enhance post-earthquake hospital functionality. Calibration of the component fragility functions with site-specific installation conditions is a current research topic under consideration by the authors.

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6 REFERENCES

Botting, R. and Buchanan, A. 2000. Building design for fire after earthquake. 12th World Conference on Earthquake Engineering. Auckland, New Zealand, Paper no. 1569.

Bruneau, M. and Reinhorn, A. 2007. Exploring the concept of seismic resilience for acute care facilities. Earthquake Spectra, 23(1), pp.41-62.

Cimellaro, G. P., C. Fumo, A. M. Reinhorn and M. Bruneau. 2009. Quantification of disaster resilience of health care facilities. Buffalo, NY: Multidisciplinary Center for Earthquake Engineering Research (MCEER), 194 p.

CUSM. 2017. Hôpital général de Montréal. Montréal: Centre universitaire de santé McGill. <http://cusm.ca/new-muhc/page/hopital-general-montreal>.

EERI. 2009. The Mw 7.6 Western Sumatra earthquake of September 30, 2009. EERI Special Earthquake Report - Learning from earthquake. Oakland: Earthquake Engineering Research Institute. <http://www.eeri.org/site/images/eeri_newsletter/2010_pdf/Chile10_insert.pdf>.

EERI. 2010. The Mw 8.8 Chile earthquake of February 27, 2010. EERI Special Earthquake Report - Learning from earthquake. Oakland: Earthquake Engineering Research Institute. <http://www.eeri.org/site/images/eeri_newsletter/2010_pdf/Chile10_insert.pdf>.

Eidinger, J.S.E. 2009. Fragility of Non-structural Components for FEMA Benefit Cost Analysis. R88.02.01 Rev. 0.: G&E Engineering Systems Inc.

FEMA. 2012. Seismic Performance Assessment of Buildings, Volume 1 – Methodology, FEMA P-58-1, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

Filiatrault, A., A. Aref, M. Bruneau, M. Constantinou, G. Lee, A. Reinhorn and A. Whittaker. 2003. MCEER's Research on The Seismic Response Modification of Structural and Non-Structural Systems and Components in Hospitals. Coll. « Seismic Retrofit of Acute Care Facilities », 25 p.

Filiatrault, A. and Sullivan T. 2014. Performance-based seismic design of nonstructural building components: The next frontier of earthquake engineering. Earthquake Engineering and Engineering Vibration, vol. 13, nº 1, p. 17-46.

Mousavi, S., Bagchi, A. and Kodur, V.K. 2008. Review of post-earthquake fire hazard to building structures. Canadian Journal of Civil Engineering, 35(7), pp.689-698.

Myrtle, R.C., S.F. Masri, R.L. Nigbor and J.P. Caffrey. 2005. Classification and prioritization of essential systems in hospitals under extreme events. Earthquake Spectra, vol. 21, no 3, p. 779-802.

NCREE. 2010. The ML 6.4 Taiwan Earthquake of March 04, 2010. «Reconnaissance activities »: National Center for Research on Earthquake Engineering.<http://www.eeri.org/site/images/eeri_newsletter/2010_pdf/Chile10_insert.pdf>.

NRCC. 2015. National Building Code of Canada. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa.

Porter, K. and K. Ramer. 2012. Estimating earthquake-induced failure probability and downtime of critical facilities. Journal of business continuity & emergency planning 5(4): 352-364.

Porter, K.A., S. Krishnan and X. Xu. 2006. Analysis of Simultaneous Operational Failure of Critical Facilities due to Earthquake, for a California Utlity. EERL 2006-01. Pasadena, California: California Institute of Technology.

Porter, K.A., E. Johnson, M. Zadeh, C. Scawthorn and S.J. Eder. 1993. Seismic Vulnerability of Equipment in Critical Facilities: Life-Safety and Operational Consequences. Coll. Technical Report NCEER, NCEER-93-0022. Buffalo, NY: National center for earthquake engineering research (NCEER), 368 p.

Scawthorn, C., J.M. Eidinger and A.J. Schiff. 2005. Fire following earthquake. National Fire Protection Association, American Society of Civil Engineers Publications.

Schultz, C.H., K.L. Koenig and R.J. Lewis. 2003. Implications of hospital evacuation after the Northridge, California, earthquake. The New England journal of Medicine. Vol. 348, no 14, p. 1349-1355. <http://www.nejm.org/doi/pdf/10.1056/NEJMsa021807>.

Shinozuka, M., Grigoriu, M., Ingraffea, A.R., Billington, S.L., Feenstra, P., Soong, T.T., Reinhorn, A.M. and Maragakis, E., 2000. Development of fragility information for structures and non-structural components. MCEER Research Progress and Accomplishments, 1999, pp.15-32.

Tian, Y., 2013. Experimental seismic study of pressurized fire sprinkler piping subsystems. Ph.D. thesis. State University of New York at Buffalo.

Youance, S., Nollet, M.J. and McClure, G. 2016. Effect of critical sub-system failures on the post-earthquake functionality of buildings: A case study for Montréal hospitals. Canadian Journal of Civil Engineering, 43(10), pp.929-942.

Zolfaghari, M.R. and Jahanbakhsh, S. 2012. Development of Seismic Fragility Curves For Hospital Equipment. 15th World Conference on Earthquake Engineering, Lisbon, Portugal.