Post-earthquake functionality of critical facilities: A hospital case study

S. Youance & M.-J. Nollet
Department of Construction Engineering, École de technologie supérieure, Université du Québec

G. McClure
Department of Civil Engineering and Applied Mechanics, McGill University

SUMMARY

This paper investigates the post-earthquake functionality of hospital buildings in Montreal, Canada by taking into account the interdependencies between the structural framework and the various nonstructural components and lifeline services. Health care facilities are classified as post-disaster systems in most building codes and are therefore required to be fully operational and safe during and after an earthquake. The main objective of this research is to develop a comprehensive methodology to evaluate the post-earthquake functionality of individual hospital facilities, in opposition to existing methodologies used in "urban scale" models. The hospital used as a case study is a complex built in 1954. It is described through its logical functionality scheme including a simple consideration of the lifeline services at this stage of the research. The seismic vulnerability of each group of components (structural, nonstructural and interfaces with utilities) is evaluated in terms of resistance and functionality according to Canadian standards.

Keywords: life safety, system interdependencies, nonstructural elements, fault-tree analysis

1. INTRODUCTION

Seismic risk is the product of seismic hazard, building vulnerabilities, and associated social and economical losses. Because of the high risk of casualties, FEMA (Federal Emergency Management Agency) estimates that earthquakes are one of the most devastating causes of disaster a hospital may face (FEMA, 2003). Specific earthquake-resistant design provisions for new hospital facilities were added over the years in many building codes, especially in high seismic risk regions. Following damages recorded during the M_w 6.7 San Fernando Earthquake (1971), the State of California enacted the *California's 1973 Hospital Safety Act*, which required that acute care hospitals withstand a major design-level earthquake and remain functional. After the 1994 Northridge earthquake (M_w 6.7), this law was amended to strengthen seismic requirements for hospitals. Since then, continuous efforts have been made in seismic design to ensure the structural integrity of hospitals exposed to high seismic hazards. However, hospital buildings built before the application of modern standards and specifically the nonstructural components of most hospitals present high seismic vulnerability as observed during recent earthquakes in California, Indonesia, Chile, and Taiwan (EERI, 2009; 2010; Myrtle *et al.*, 2005). The functionality of many hospitals was impaired by structural, nonstructural and lifeline failures and some of the buildings had to be evacuated even though these hospitals were the primary sources of trauma care in the region struck by the earthquake. Nonstructural damage such as piping, fire protection and ceiling system collapses and power outrages could be considered as the most critical. Therefore the overall hospital serviceability depends on the performance of multiple elements and interacting systems rather than on the sole fact that the structure remains standing. Post-earthquake functionality of critical facilities such as hospitals is therefore achieved by ensuring high performance levels for different functions considered as essential.

This paper presents, through a case study of a Montreal hospital, a framework to evaluate the post-earthquake functionality of critical facilities, with a focus on the fire protection system as an example. Fire protection systems are essential and their malfunction requires evacuation of the building.

Although structural damage resulting from ground shaking is often the main concern in seismic engineering, fire following an earthquake or damage to the fire protection system could result in loss of human life. The proposed framework for the evaluation of the post-earthquake functionality of hospital facilities relies on the accurate identification of the main parameters triggering a malfunction of the essential hospital systems through a qualitative fault tree analysis. This work represents the first attempt to systematically assess the overall post-earthquake functionality of a Montreal hospital.

2. OVERVIEW OF MONTREAL HOSPITALS

This research follows a pilot study on post-earthquake functionality of six Montreal hospitals as part of the Canadian Seismic Research Network (CSRN) activities and in collaboration with the Agency for Health and Social Services of Montreal (McClure *et al.*, 2010). Seismic risk assessment of several typical operational and functional components (OFCs) of the hospitals was conducted in accordance with a parametric procedure described in CAN/CSA S832-06 *Seismic risk reduction of operational and functional components (OFCs) of buildings.* (CAN/CSA, 2006). Overall, the risk level assigned to most evaluated OFCs (53%) was moderate while it was considered high for nearly 27% of them. These results have highlighted the importance of better defining the seismic vulnerability and risk of Montreal hospitals, in terms of functionality and life safety. This OFC risk assessment process is considered as a basic step in the development of a comprehensive assessment of post-earthquake functionality of buildings, taking into account interdependencies between the building structure, the building content and its nonstructural components and subsystems, and their interfaces with lifelines.

According to the last annual report of Montreal's Health and Social Services Agency (Gouvernement du Québec, 2012), the Montreal Island population, estimated to 1.9 million inhabitants, received health care services from 88 institutions at 400 facilities and service points distributed throughout its 499 km^2 territory. Among those, 33 institutions are categorized as general and specialized or ultra-specialized care hospitals offering emergency services, nursing, paediatric and mental health care and other services including medical imaging and nuclear medicine or rehabilitation services (see Fig.2.1). Approximately 89000 people are working in the health network in Montreal.

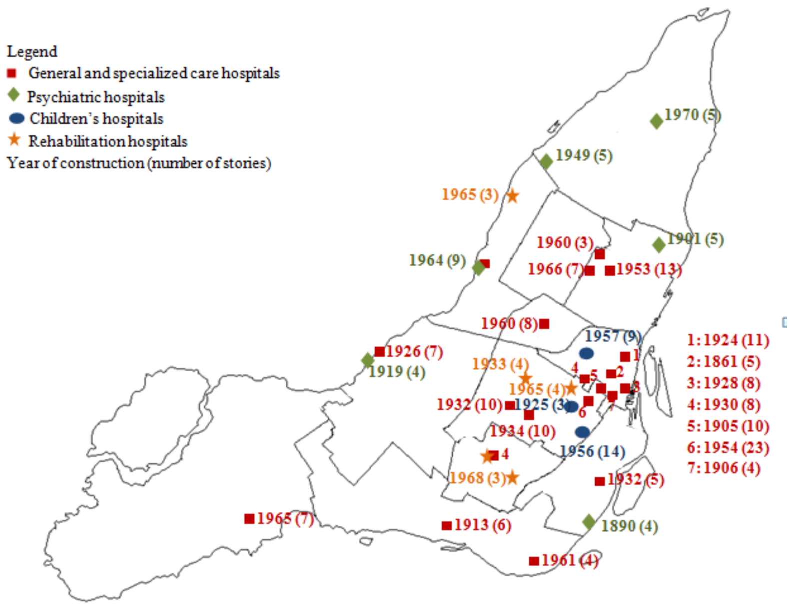

Figure 2.1. Distribution of 33 hospitals facilities on the Island of Montreal

The 33 hospitals facilities 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. Typically they are large buildings of low to medium height (up to 14 stories) with few exceptions (see Fig. 2.1). 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 rectangular in shape with few vertical or horizontal irregularities. Heavy load-bearing masonry walls are used in the oldest constructions, built before 1920 (22% of buildings): this system is seismically vulnerable according to the report of damages due to the 1988 Saguenay earthquake (M_w 5.9) (Tinawi *et al*., 1990).

3. FRAMEWORK FOR POST-EARTHQUAKE FUNCTIONALITY ASSESSMENT OF HOSPITALS

3.1. Hospital facilities as a functional system

A hospital can be defined as a complex and interacting system comprising structural building components, quantity of nonstructural components (including building content) themselves organised in complex systems, and personnel providing services (see Fig. 3.1). This system should adapt to external changes in its environment and to extreme events, such as earthquakes, that could drastically modify its operational and functional conditions. The aim of the proposed procedure is to assess the seismic risk associated to the hospital system excluding the personnel operations.

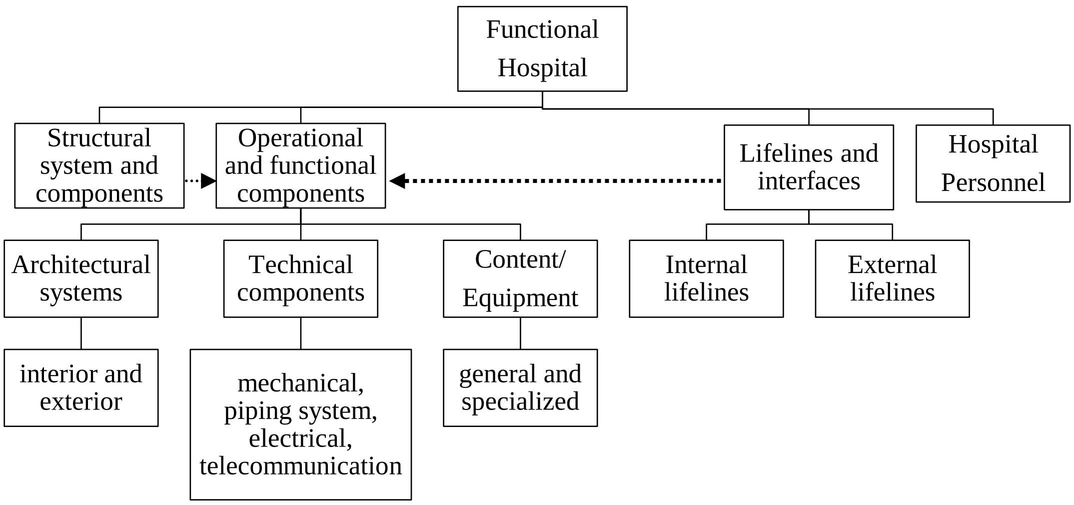

Figure 3.1. Functional components of a hospital

In Figure 3.1, it is seen from a bottom-up reading that post-earthquake hospital functionality is provided by the good performance of its interdependent and interactive operational and functional systems and is determined by: 1) the seismic vulnerability assigned to individual OFCs; 2) the seismic vulnerability of the building structure and its load-bearing components; 3) the vulnerability of its lifeline interfaces (electricity, water, gas, telecommunication systems); 4) which are in turn directly influenced by seismic hazard and geotechnical site effects. This interdependency of seismic performance involving the building structure, the OFCs and their subsystems, and the lifeline interfaces, is represented by a dashed line in the figure. It is typically complex and the system functionality cannot be achieved by a simple sum of subsystem or component functionality indices.

Many considerations arise when assessing the post-earthquake functionality of a hospital such as: the common cause of failure as trigger event, the failure sequence, the redundancy available in the system, the identification of critical functions and their weakest links/paths, for example. In this perspective, each component should be assessed as a part of the overall system and not in isolation. The challenge is 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. It is suggested here to construct the functional hospital system using a deductive system analysis (DSA) (US Nuclear Regulatory Commission, 1981). If a critical system fails, the consequence will be the hospital post-earthquake "non-functionality". The objective is therefore to identify what individual OFCs and subsystems contribute to this failure. From an analytical standpoint there are several overriding advantages to failure deductive analysis, and the two main ones are that the complete failure state is easier to define compared to an efficiency analysis chain, and the size of the deductive chain is relatively limited or finite. The DSA method selected in this research is the Fault Tree Analysis (FTA), which is commonly used in risk analysis of complex systems modelled by random variables (Hasofer *et al.*, 2007).

A fault tree is a logical graph representing the various combinations of basic failure/malfunction events susceptible to occur in a complex system and their consequences on the functionality of the whole system. The relationship between an Input (or lower event) and the Output (or higher event) is identified as a Boolean gate (.AND. / .OR.). The .AND. gate represents relationships between all the input faults in such way that when the first failure occurs, the system will automatically rely on the next input event in the row. The .AND. gate expresses a more robust system. This will be further illustrated in section 5.

In this study, the Inputs to the gates are the failure/damage states caused by an earthquake, as defined based on previous observations of earthquake damages to hospital facilities. Once the fault tree is constructed, a qualitative evaluation is carried out to determine the minimum cut sets (weakest tree branches). The chart in Fig. 3.2 shows the analytical process adopted in this research and adapted from the Infrastructure Risk Analysis Model (IRAM) described in Ezell *et al.* (2000).

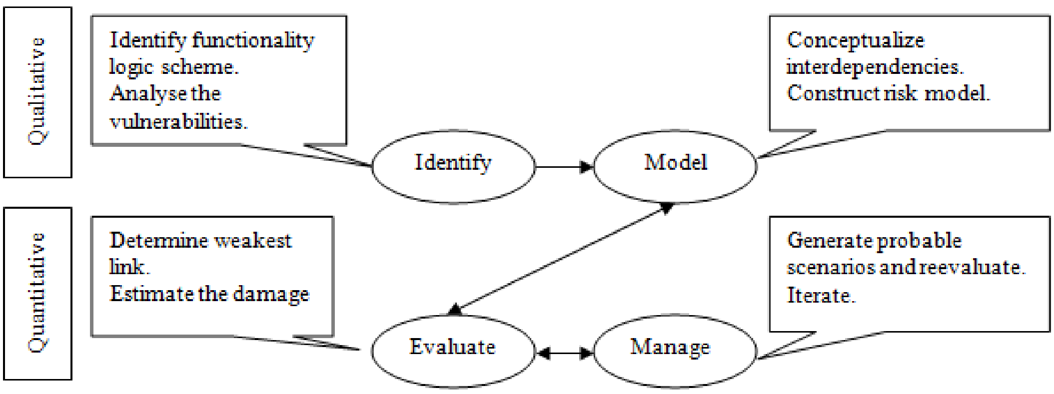

Figure 3.2. Fault-tree analysis process

3.2. Risk associated to fire following earthquake and system response

Scawthorn *et al.* (2005) have identified three key factors that may cause a fire after an earthquake. Mainly, a fire outbreak is a random event due to: 1) high peak ground acceleration causing breakage or overturning of building contents that may explode or create short circuits or arcing, 2) excessive structural deflections resulting in abrasion or other damage to electrical wiring, and 3) rupture of underground lifelines such as natural gas lines which provides a source of ignition. This is particularly worrisome in the moderate seismicity Montreal area where the high frequency range of the uniform hazard earthquake spectrum is associated with relatively high peak ground and spectral acceleration values exceeding 0.65 g while ground displacements are typically very small due to the absence of surface or near-surface fault systems. Moreover, many studies such as Tinawi *et al.* (1990) and Lamontagne (2008) have confirmed that the presence of alluvial formations of varied depths (from shallow – less than 30 m to deep) on top of rock or stiff soil is widespread on the Montreal island, which locally amplify the effects of seismic waves and consequently increase the seismic hazard.

The fire protection system is one of the most challenging for building functionality design. Since both fire and people thrive on oxygen, potential conflicts can be generated between fire protection systems and heating, ventilation and air-conditioning (HVAC) systems, and safe egress systems (Stein and Reynolds, 1992). It is interesting to highlight the common performance objectives of both post-earthquake functionality and fire protection: life safety, integrity of the building structure and continuity of the building operations. The first two performance objectives are addressed by the minimum requirements of most building codes, while emphasis on functionality is only beginning to be addressed in practical design. The following paragraphs present a brief overview of the hospital expected response in order to reach the required performance levels with reference to fire protection.

3.2.1. Life safety

Partial or global evacuation of building occupants could be a reasonable goal to ensure life safety, and clear horizontal pathways to vertical exits should always be available for safe egress. The minimum requirements for fire-enclosed hallways, fire-rated doors, continuing stairs and their dimensions and restrictions (non-use of elevators) are specified by the codes. Another point to consider is the functionality of the fire alarm, smoke detectors and HVAC system that helps maintain air quality.

Hospital evacuation in the event of an earthquake is a major process where the safe and orderly egress of patients is the main concern. Several interrelated decisions (e.g.: selecting destinations, first evacuated mobile inpatients and means of transportation, planning *in situ* shelters or safe areas for others) have to be made in a limited resource environment and in coordination with the overall response to the earthquake. The complexities of hospital evacuation arise mainly from the size and interaction between each decision (Taaffe *et al.*, 2005). However, experiences from past events have demonstrated that the affected facilities were successfully evacuated and continuous care has been provided to all patients (Schultz *et al.,* 2003). The development of robust evacuation strategies is therefore essential.

3.2.2. Structural integrity

Early function of the fire system is paramount to protect structural integrity during and after a strong earthquake, as fire outbreaks mostly happen within the first hour aftermath (Botting and Buchanan, 2000). Delays in reporting fire and in the early response could easily take place due to nonstructural damages such as failure of communication equipment, fire protection system and piping. Also, hospitals contain hazardous materials that can activate the fire. Therefore structural integrity is ensured only if the building and its components are adequately designed for both earthquake and fire hazards and their interaction.

3.2.3. Continuity of the building operations

This performance level can only achieved after the previous two are met. The common failure modes of fire protection systems, their potential causes and consequences are well known and documented (Bagchi *et al.,* 2008; Botting and Buchanan, 2000; Scawthorn *et al.,* 2005; Schultz *et al.,* 2003; Taghavi and Miranda, 2003). These references pointed to the need for developing guidelines and evaluation tools.

4. HOSPITAL CASE STUDY

4.1. Global description of hospital facilities

The hospital considered in this case study is the Montreal General Hospital (MGH), a key facility near downtown Montreal. The hospital is part of the McGill University Hospital Centre (MUHC), a network of research hospitals. In addition to providing a wide range of acute health care services, it is one of the two trauma centres on the Island that can receive inpatients in highly critical conditions from the whole province of Québec. In 1998, the MGH was the subject of a functional review of both the structure and quality of services in view of a re-development of the site (Decarel and Dessau, 1998), which is currently near completion. It should be mentioned that no formal seismic evaluation, structural or nonstructural, has been made up until now. The necessary data to perform the present post-earthquake functionality evaluation were obtained from site inspection, review of previous reports and study of drawings.

Built in 1954 on the South-West side of Mount Royal, the hospital campus is composed of six blocks spatially organized in orthogonal directions and founded on bedrock. Figure 4.1 illustrates the main plan of the hospital and the elevation of its main entrance (elevation J-J) showing the sloped ground line.

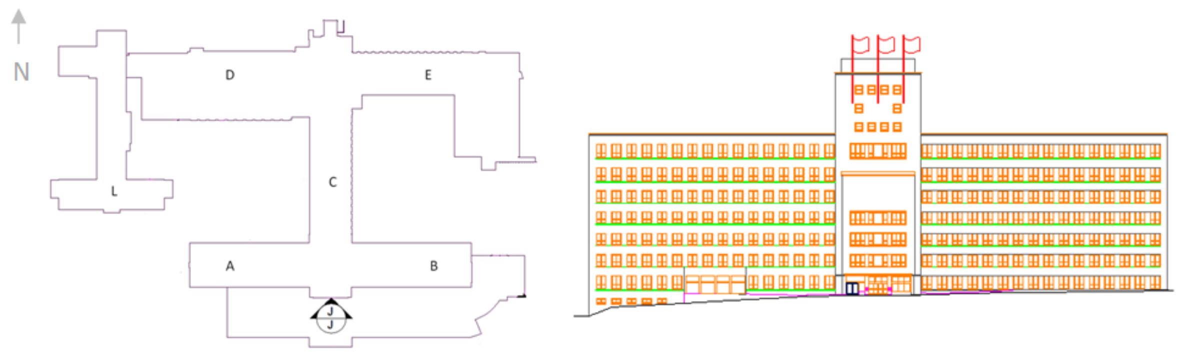

Figure 4.1. Main plan and elevation J-J of Montreal General Hospital

Each block or aisle is associated to different services: the emergency room and supports services, in Blocks A and B (7 floors); surgery in Block C (10 floors), inpatients units in Blocks D and E (19 floors), cancer research in Block L (15 floors). The East part of Building E (base of L shape) holds all essential mechanical and electrical components on its first three levels. Building E is connected to Blocks C and D from level 4 and above. The central tower (23 floors) located at the intersection of Blocks C, D, and E houses administration offices.

4.2. Description of the structural system

The structural system of all blocks consists of steel braced frames with W-shape columns, with a reinforced concrete flat slab. The diagonal bracings are made of symmetric steel plates and angles, and braced bays are located at the perimeter of each block.

In 1964, three floors were added to blocks A, B and C. In 1991, similar additions were made to block L and its lateral load resisting system was upgraded to meet the current building code seismic requirements (NBC 1990). Several shear walls were added in the stairwells and elevator shafts (Decarel and Dessau, 1998).

4.3. Identification of fire protection system

The fire protection system has been designed based on the building code of the time (1954), with no requirement for sprinkler system at every floor. Since then, improvements have been made and a specific protection plan in line with current standards is being established. The complete evacuation of the hospital in case of fire is considered impractical given its acute care vocation and the limited mobility of its patients. The response procedure will therefore focus on early response from the hospital staff as soon as an alert is issued. It should also be considered that the safe evacuation of such facilities is tributary to the hour of the day the disaster strikes, the building occupants (staff and inpatients) and provision of services varying in function of time and demand. The physical life safety system is composed of elements required by the building code (fire safety section). Seismic vulnerability of these operational components is taken into account in the fault tree where these components are considered as Inputs, as discussed next.

5. FAULT TREE CONSTRUCTION FOR POST-EARTHQUAKE DYSFUNCTION

To assess the post-earthquake dysfunction of the hospital, considered as the “undesirable event” two subsystems have been considered in this first stage of the study: the life safety of occupants (gate 1, GT1) or “unsafe partial evacuation” and the building structure integrity (gate 2, GT2) or “unsafe structure”. The two corresponding fault trees are presented in Figures 5.1 and 5.2.

In the construction of the fault tree, the basic bottom-up approach is considered: 1) failure mechanisms related to direct damage events triggered by an earthquake (events EV1 to EV6 for example in Fig. 5.1); 2) failure modes specifying what subsystem is affected; and 3) failure propagation effects on higher-level building functions, and, at the top, the post-earthquake functionality. Any of the component failures could also be considered as a top event since the lower levels are the causes of component failures and a more refined arborescence could be established as events leading to a gate represented by a triangle (gates GT4, GT5 and GT11 in Fig. 5.1). In Figure 5.1, the hospital is initially considered with physical components that are potentially vulnerable during earthquakes. The possible dysfunction of these components defines the basic events at the lowers levels. All fault events (Gates GT1, GT3, GT9 and GT10) may be triggered by one component failure, so .OR.-gates are considered.

The good performance of both HVAC (by confining fire cells) and life support systems (gates GT4 and GT5) allows the required time for safe evacuation of mobile patients and maintaining bedridden patients’ in safe conditions until the fire fighters take over the rescue staff. Failure of the active fire protection system is included in the second branch of the fault tree (Fig. 5.2) in order to evaluate its interaction with the structure, the OFCs and the lifelines (gate GT6).

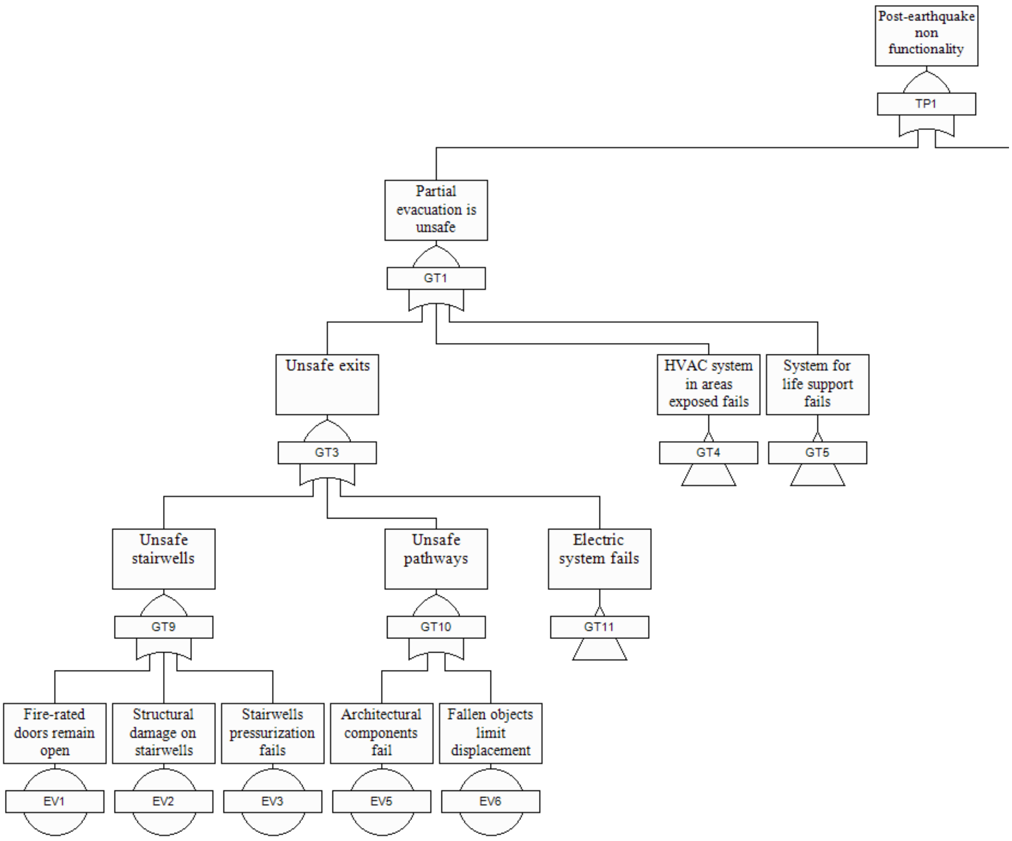

Figure 5.1. Fault tree for “unsafe partial evacuation”

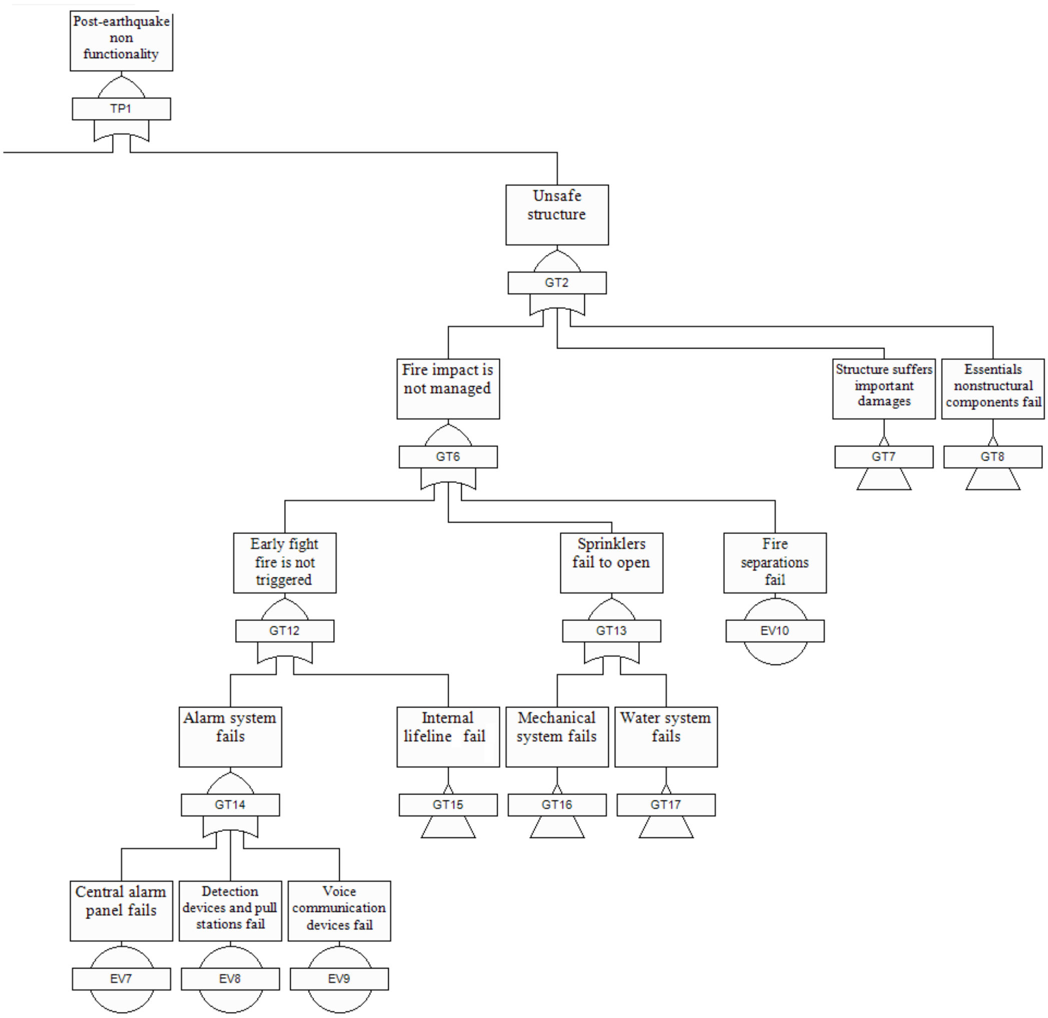

Figure 5.2. Fault tree for "unsafe structure"

6. FRAMEWORK FOR THE ANALYSIS OF "UNSAFE STRUCTURE"

6.1. General

Structural components and subsystems are designed for a required *fire-resistance rating* that allows safe evacuation and thus avoiding progressive collapse. Earthquake-induced damage to the structure makes it more vulnerable to subsequent fire by reducing the load-bearing capacity and adding new stresses due to second order P-Δ effects induced by excessive drifts, for example. Of course, even when no fire follows the earthquake, the seismic vulnerability of the structure must be assessed.

Considering the fault tree for "unsafe structure" (see Fig. 5.2), a detailed analysis could be conducted since deterministic events are being considered: fire protection failure (gate GT6), structural damage (gate GT7) and failure of essential nonstructural components (gate GT8). The failure of nonstructural components (central alarm, detection devices, pull stations and fire separations) is also considered as Input leading to the unmanaged fire impact (basic events EV7 to EV10). Gates GT15 to GT17 related to internal and external lifeline failures are not developed here.

The following paragraphs present a simplified analysis of the fault trees. Considering the interdependency and interaction of several systems, this analysis is in fact an iterative process. For example, once the structural performance analysis is completed, the functionality of the fire protection system is reassessed, like the integrity of non-structural components.

6.2. Fire impact management

In a critical facility it is essential to limit or prevent the spread of fire. The earliest the fire is managed the more efficient the system will be. The quality of the response depends on internal factors such as the rescue staff mobilization once the alarm is triggered and the strength (and fire rating) of all OFCs and lifelines. Constructing a risk model, the weakest link appears to be the building/rooms housing operational equipment where critical services are provided, i.e. Block C in the case study.

6.3. Structural damage

To assess the risk of structural damage in the FTA, rapid visual screening procedures are applied to the hospital blocks. These procedures allow obtaining an approximation of the seismic structural vulnerability and therefore identifying if potential structural damage could hinder the functionality of the fire protection system. A limited ductile braced-frame system is considered in the case study.

Three different score assessment procedures were used on Blocks A, B, C and E (IRC, 1992; Karbassi and Nollet, 2008; Tischer, 2012). The last two methods are based on FEMA154 and take into account the presence of horizontal irregularities in Block E (L-shape in Fig. 4.1). Table 6.1 presents the results of these evaluations with the interpretation of the score in terms of moderate or moderate to high seismic vulnerability. To ascertain this evaluation the base shear ratio of each building is calculated according to the 1953/1960 NBC requirements and those of 2010 NBC. The three screening methods yield identical vulnerability for Blocks A to C, while Block E appears to be the most vulnerable when horizontal irregularities are considered.

Table 6.1. Assessment of structural vulnerability

	IRC93 score	Karbassi and Nollet's score	Tischer's score	V_R ratio
Block A	13.61 (moderate)	4.1 (moderate)	1.2 (moderate)	42.4%
Block B	13.61 (moderate)	4.1 (moderate)	1.2 (moderate)	42.4%
Block C	13.61 (moderate)	4.1 (moderate)	1.2 (moderate)	41.3%
Block E	13.61 (moderate)	3.4 (moderate to high)	0.7 (moderate to high)	Not applicable due to L-shape; a dynamic analysis is required

This first level assessment highlights the need for further analysis based on accurate dynamic properties of buildings. Ambient vibration measurements were performed on hospital blocks and extraction of the dynamic properties of the buildings is underway. Then, dynamic analysis will be performed to quantify damages under three earthquake scenarios of seismic demands, with probability of exceedance of 2%, 10% and 50% in 50 years.

6.4. Vulnerability assessment of nonstructural components

In the event of moderate earthquakes, buildings founded on rock will suffer limited deformation and the vulnerabilities are mostly associated to acceleration-sensitive nonstructural components. Inertia forces will trigger pendulum motion of suspended components, and sliding and overturning of floor-mounted components with insufficient base-restraints. Damage reviews from past earthquakes have shown that building safety depends primarily on the vulnerability of key nonstructural components and lifelines (gate GT8 in Fig. 5.2). The seismic vulnerability of each typical component is evaluated in terms of resistance and functionality according to the parametric method described in CSA S832-06.

7. CONCLUSION

This paper highlights the significance of a holistic analysis of the hospital system with detailed identification of its components and subsystems and their interactions and interdependencies. Once the fault tree representing the system has been constructed, a qualitative analysis is performed to extract potential dysfunctions. Whilst the methodology for post-earthquake hospital functionality assessment is yet to be fully developed, the procedure presented is original.

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