

Developing an Integrated System for Seismic Risk Analysis of Critical Hospital Facilities

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Research Objectives

This paper describes an approach used to develop retrofit strategies for hospitals and other critical facilities in low to moderate seismic hazard zones, where strong earthquakes are infrequent, but if they should occur, the consequences would be high. Hospitals in New York State and other urban centers in the eastern U.S. fall into this category, where seismic retrofit requires information on the impact of losing medical services after a destructive earthquake. A team of MCEER researchers is currently developing an approach to address this task. It is a truly multidisciplinary effort, with team members from a variety of disciplines including engineering, seismology, structural dynamics, risk and reliability analysis, manufacturing process engineering, computer simulation, urban and regional planning, and economics. When this research task is completed, it will be united with MCEER's general hospital project to develop seismic retrofit strategies.

Making a decision to seismically retrofit a hospital facility in New York State typically involves different considerations than for facilities located in California. This is primarily because earthquakes are not as likely in New York State, whereas, other natural and manmade hazards and threats are perceived to have equal or even higher risks. Following the five-step decision making process for performing a systems evaluation of a hospital, in New York State described by Lee et al., 2001, the benefits of choosing a seismic retrofit must be objectively compared with other options such as creating a risk plan, developing emergency response procedures, using risk aversions or simply accepting the risks. The core of this analysis process is the quantitative modeling of the relationship between the hospital operation and its supporting resources (human and facilities) as illustrated in Figure 1. The Forrest model is considered to be a suitable tool for presenting a system model of the relationships within a hospital.

Building on last year's research effort on seismic retrofit strategies for hospitals in New York and throughout the Eastern United States (Lee et al., 2001), a framework for a multi-layer platform has been developed by the research team. This platform focuses on the resources provided by facility

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Previous Summaries

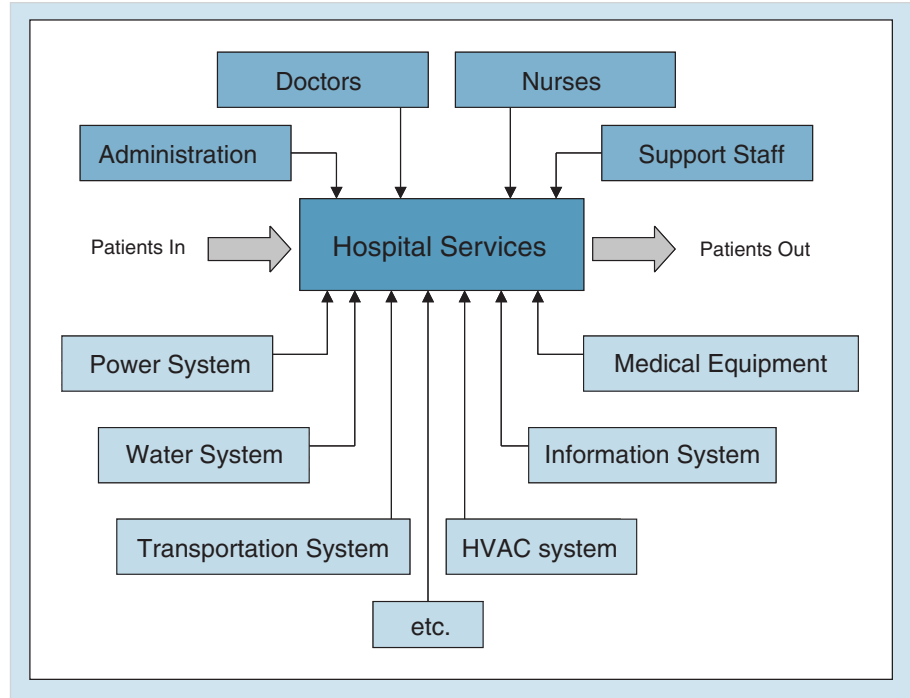
2000-2001:

Lee et al.,

http://mceer.buffalo.edu/publications/resaccomm/0001/rpa_pdfs/12lee-hosp_graphics.pdf

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■ Figure 1. Model of the Relationship between Hospital Operation and Supporting Resources

systems, such as power, water, HVAC, equipment, etc. It is an important step towards developing a comprehensive evaluation procedure for a hospital network system. Currently, a specific case study is being carried out in a hospital located in Central New York State.

Seismic Impact to Hospital Operations

In many moderate seismic zones such as New York State, critical hospital facilities face risks of facility

system breakdowns caused by an earthquake. In contrast to California, the probability that a significant earthquake will occur in these moderate seismic zones is not as likely, but the cost of collapse could be much higher due to the lack of protective measures. It follows that the consequences of building damage or collapse may range from slight to complete collapse, and damage to or caused by nonstructural components may also fall in a wide range. Therefore, as we have encountered in all five

Hospital administrators, building owners and other stakeholders in regions of minor to moderate seismicity can use the evaluation system for retrofit strategies to make optimal risk management decisions. Resources for hazard mitigation of all types are limited, and a decision-making method based on solid cost-benefit principles will be a valuable tool in planning for multi-hazards, including earthquakes.

hospitals studied in New York State, the decision to proceed with seismic retrofit or emergency preparations requires a true understanding of the seismic risk factors associated with the hospital and how such an earthquake would impact daily operations. As we proposed in 1999, (reference?) to acquire true risk information, a systematic way to evaluate the seismic hazard impact to the hospital operation is needed. This evaluation method could then also be applied to other natural hazards.

As described in Lee et al., (2001), a hospital is a service organization where medical services are provided to patients. For each medical service provided to a patient, many supporting resources are needed, including human resources (medical doctors, nurses, staff, administrators) and physical facility resources (power, water, HVAC, medical gas, information, medical supplies). Fig-

ure 1 shows how an earthquake will impact a hospital's ability to deliver medical services. First, a hazard event will directly impact the structural system, the lifeline systems, medical facilities and medical services in terms of structural damage, limitation or shortage of supplies, and increased patients; second, the structural responses will result in non-structural systems damage; third, the lifeline system damage will influence the proper operation of medical equipment; and fourth, collectively, the damage or inoperability of the building structure, lifelines, and/or medical equipment will impact the overall delivery of medical services.

To understand the impact of an earthquake from the occurrence of the hazard event to the medical services, a multi-layer integrated platform is developed to assess and evaluate the seismic risk.

Collaborative Partners

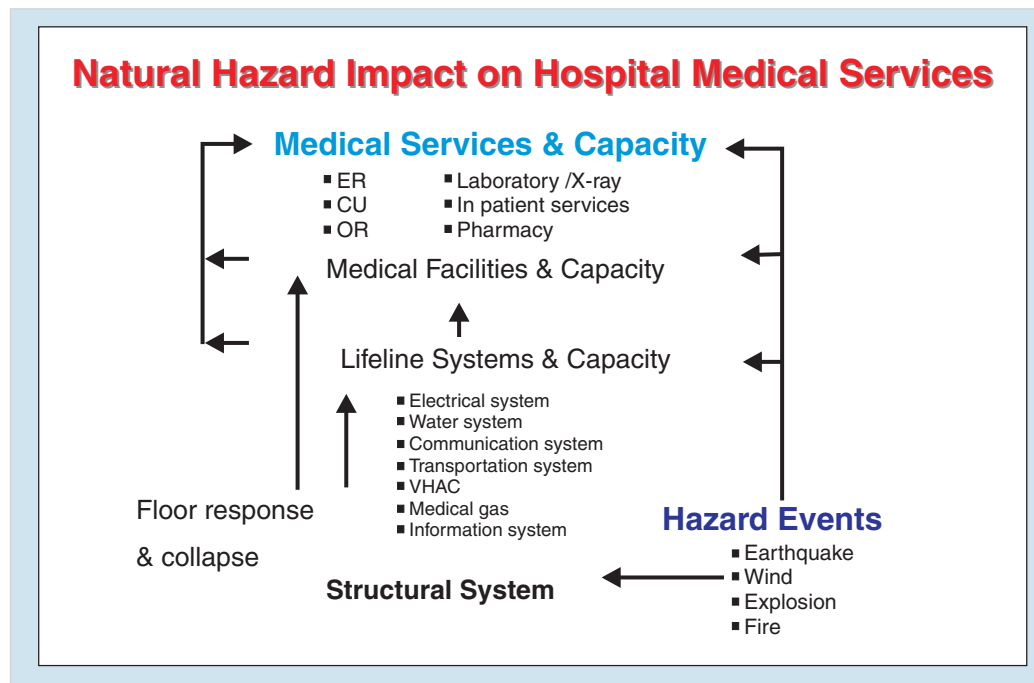
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■ Figure 2. Hazard Impact on Hospital Services

A Platform for Risk Evaluation of Critical Hospital Facilities

The platform for risk evaluation of critical facilities is intended to integrate the structural and major non-structural systems in a hospital and provide seismic risk analysis for the integrated facility. As illustrated in Figure 3, the platform consists of five category layers: hazard, structural system, major non-structural systems, risks and business services. In the following subsections, the functions of each layer are described.

Hazards

Hazards are the cause of disaster consequences. In order to quantitatively assess different hazards, a uniform data process is used. The process requires three types of data inputs: physical parameters, characteristics and influential factors. Physical parameters provide the quantitative values of the hazard conditions such as ground acceleration, velocity and displacement for an earthquake hazard. For each selected physical parameter, there is a corresponding list of characteristics that further describe its condition. For instance, in seismic hazard

assessment, the peak amplitude, frequency components and duration of ground acceleration are three critical characteristics of the hazard conditions. A given physical parameter and its critical characteristics provide the basis for a quantitative assess-

ment of the hazard. However, final determination often depends on external, or influential factors. For seismic hazards, influential factors include the source of ground motion, fault, distance from the epicenter, site effects, and so on.

Structural System

The structural integrity and safety is the basic warranty for the functionality of all major non-structural systems and medical services in the hospital. In general, the structural layer deals with essential information from the major load carrying members such as the columns and beams and their material, size, construction quality, and spatial distribution. A structural system model, such as a finite element (FE) model, can be derived from the basic structural member information. Such a model can be used to evaluate the structural integrity under various given hazard loads. Or, it can be used to generate floor or area responses to evaluate the response of supported nonstructural systems.

In the structure layer, the design seismic load plays a key role in the structural evaluation. In the IBC 2000 code, hospital structures are classified in seismic use group III, and have the highest importance factor, 1.5. In contrast, for ordinary buildings in seismic use group I, the importance factor is 1.0. For seismic rehabilitations, FEMA 356 (pre-standard and commentary for the seismic rehabilitation of buildings) offers the BSO (basic seismic objective) performance levels defined as OP (operational) for earthquakes of 50% exceedance probability in 50 years, IO (immediate occupancy) for earthquakes of 20% exceedance probability in

| |
|-------------------------------------|
| Hazards |
| Structural System |
| Major Non-structural Systems |
| Risks |
| Medical Services |

■ Figure 3. Five Layers of the Integrated Platform

50 years, LS (life safety) for earthquake of 10% exceedance probability in 50 years (BSE-1), and CP (collapse prevention) for earthquakes of 2% exceedance probability in 50 years (BSE-2). According to FEMA 356, rehabilitation design for BSO is expected to produce earthquake performance similar to that desired for new buildings in seismic use group I. Therefore, for hospital buildings, the design seismic load level is approximately 50% more than for ordinary, or regular, buildings.

The evaluation of a hospital structure performed under different hazard conditions is compared to certain pre-determined requirements. In California, under the SB 1953 bill, OSHPD (Office of State-wide Health Planning and Development) is requiring hospitals to determine the structural and non-structural system performance categories, and plan for necessary upgrades. There are five SPC (structural performance categories). This technical classification of structural performance requirements may be a useful reference for hospitals in other lower seismic hazard zones.

Major Non-structural Systems

This layer deals with detailed information about major non-structural systems, including:

- Power system
- Water system
- HVAC system
- Gas, medical gas and vacuum system
- Fire alarm and suppression system
- Communication system
- Internal transportation and egress system

- Information and data network system
- Architectural components
- Medical equipments

Although the general working principles of the above systems are the same in all hospitals, each hospital has its own unique adaptation that makes them different from the systems in another hospital. Since damage is often directly related to these differences, it is necessary to develop a hospital-specific detailed function stream flow diagram for each of the above systems along with a collection of relevant component information.

In order to understand how a component's failure influences the overall function of the system, a logic tree approach is often used to build system operability. For each component, its operation is normally dependent on several other components. By classifying these subordinate components as logic OR (redundant) and AND (essential), a system logic tree can be formed. The dependency relationship of the system to its components is thus established.

Among the non-structural components, medical equipment is a special group. They are directly related to specific medical services, and are more delicate than most components of utility systems. Therefore, protection of medical equipment will be different from that of other utility systems. In surveying several NY State hospitals, it was found that most of the medical equipments are portable. In addition, their operability most often depends on three factors: building integrity, utility supply and information networking.

Links to Current Research

This task is pursued in parallel with the other larger efforts related to acute care facilities (Alesch, Bruneau, and others). The detailed hospital facility model developed herein will characterize facilities in low to moderate seismic zones, which will complement those being developed primarily for hospitals in California.

Web Sites

MCEER Hospital Project:
<http://mceer.buffalo.edu/hospitals/>
 (Choose the Introduction tab for an overview of the project. For user controlled information, please contact Mai Tong at mtong@mceermail.buffalo.edu.)

Risks

Risks are various types of potential failure or damage. The facility-related risks can be generally assessed through survival analysis. The results of earlier studies have been published in Shinozuka, 2001; Porter et al., 1993, Grigoriu and Waisman, 1998 and Shinozuka et al., 2000. A component's failure acceleration is described as follows (Shinozuka, 2001 and Porter et al., 1993)

$$A = A_m \varepsilon_R \varepsilon_U \quad (1)$$

where A_m is the median failure acceleration, ε_R represents the inherent randomness of A , and ε_U represents the uncertainty. Both ε_R and ε_U are assumed to be unit median lognormal random variables with logarithmic standard deviation (SD), β_R and β_U .

The seismic risk of a component is measured by its fragility - the conditional probability of "failure" under a given level of seismic hazard level a (intensity of motion at the support).

$$P_{fc} = \Phi \left[\frac{\ln(a/A_m) + \beta_U \Phi^{-1}(Q)}{\beta_R} \right] \quad (2)$$

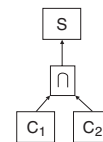
where Φ is the normal cumulative distribution function. The logarithmic SD of fc is

$$\beta_c = \sqrt{\beta_R^2 + \beta_U^2} \quad (3)$$

For instance, the fragility of a major electrical transformer under seismic hazard is a function of failure probability vs. PFA (peak floor acceleration). This function varies according to the level of confidence. However, if many uncertain factors are not clearly identified, such as, the footing condition, the anchor condition, and the quality

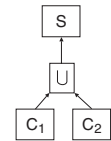
of internal components in the transformer example, then the fragility function may largely vary between low to high levels of confidence. Identifying these uncertain factors and applying proper engineering assessment and judgment may decrease the variance of the fragility function. In this regard, detailed information in the facility model plays an important role.

The system fragility can be formed by using the logic tree (fault tree) based on the dependency relationship established for components and subsystems. In particular, for each AND and OR relationship, the combined fragility will be



$$P_s = 1 - (1 - P_{c1})(1 - P_{c2})$$

$$P_s = P_{c1} P_{c2}$$



where P_{c1} and P_{c2} are the fragilities of the components C_1 and C_2 .

Annual probability of failure P_{fa} due to earthquake of any intensity

$$P_{fa} = \int_0^{\infty} \frac{-dH(a)}{da} P_{fc}(a) da \quad (4)$$

where $H(a)$ is a hazard function (measured in the occurrence probability of exceedance) of a given level of hazard (motion at support) a (measured in g).

For seismic hazard, California hospitals are required by OSHPD to evaluate their critical non-structural components and systems according to a five level NPC (Non-structural Performance Category).

Medical Services

This layer deals with patient service operations in the hospital. It analyzes the patient distribution and the services provided in each department (internal medicine, surgery, radiology, eye & throat, etc.) Using correlation and input-output analyses, one of the main features is to evaluate the dependency of medical services to the utility systems. The utility demands are delivered by the physical utility systems. The demands themselves are not attributes of the physical utility systems, rather they are requirements to the physical utility systems and are directly associated with the patient services. Therefore, demands are determined in the patient service model.

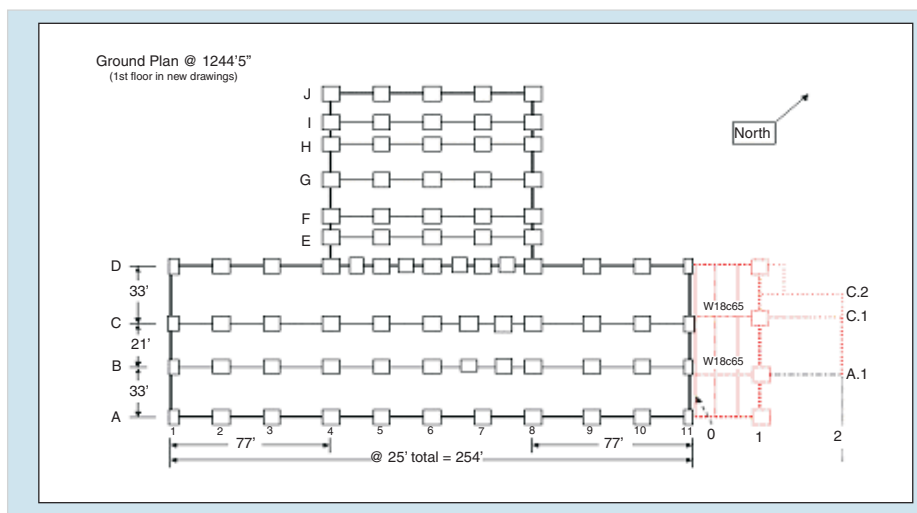
The medical services are dependent on time and spatial factors. The corresponding utility demands will vary during the day, month or season. Also, they are distributed into designated areas (OR, ER, ICU, etc.). Furthermore, during and immediately after a disaster, the type of medical services can be significantly changed by the destructive

nature of the disaster. In some cases, even without any limitation of material supply, the operational capacity of a hospital may not be sufficient to meet the overloaded demand caused by the disaster.

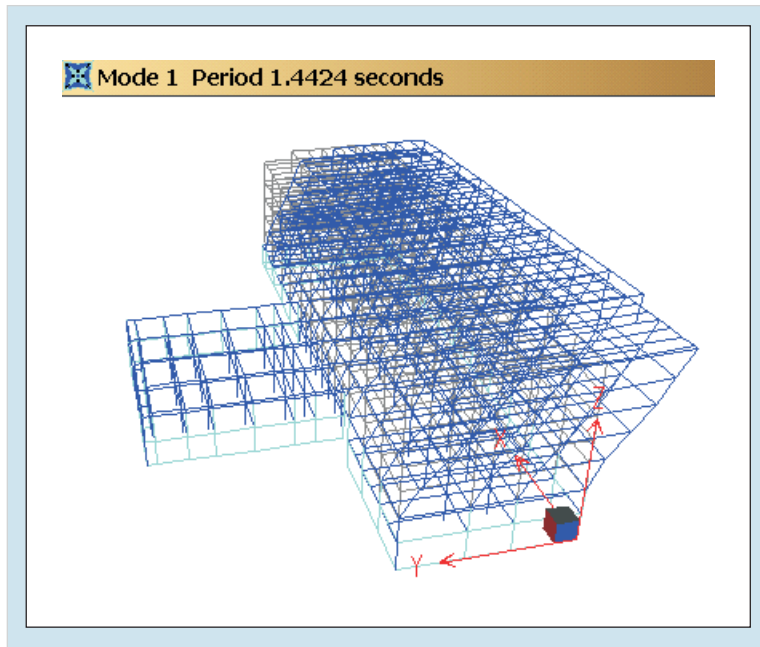
One of the research areas in this layer is the change in the dependency relationship between normal and emergency conditions. As observed in many cases, medical service procedures adopted in an emergency situation can be significantly different from normal procedures; therefore, the input-output relationship established in the normal situation is no longer valid for emergency medical service analysis. However, for a longer period of time, within a probabilistic confidence interval, the relationship may still be applicable for certain analysis.

On Going Case Study

Figure 4 shows a plan view of the hospital building that is currently being studied. This hospital is undergoing a major renovation and expansion as of 2003. Several seismic structural retrofit options are



■ Figure 4. Hospital Building Plan View - Case Study



■ Figure 5. First Mode of the Hospital Structure

under consideration to improve the main medical building's resistance to seismic hazards. One option is to add steel shear walls in both directions of the building; another is to increase the section area and reinforcement of several columns. In order to determine the benefits offered by these options and provide design load and capacity requirements, a time history analysis has been performed.

The dynamic analysis obtained from the finite element model indicates that the first major mode is in the short direction and the corresponding fundamental period is about 1.5 seconds (see Figure 5). When a design earthquake following IBC2000 is applied to the struc-

ture, several major columns appear to be severely overstressed, and should be strengthened by seismic retrofit.

However, it was found that after the structural retrofit, the seismic risks to the non-structural systems may become higher, since the strengthened building structure will have a shorter fundamental period; therefore, the non-structural systems may be subject to higher floor responses under the same earthquake.

Conclusion and Future Research

The studies related to protecting hospitals in New York State from earthquake disasters have so far developed the analytical and computational capabilities for analysis of structural and non-structural components; a GIS-based database for seismic hazard assessment, and several hospital structural models that include the property characteristics of the structures.

Some data on medical equipment and non-structural components has been collected and stored in a database. The database lacks information on the deterioration of property characteristics of these equipments and non-structural components. A future effort will concentrate on collecting this information and adding it to the database, with an emphasis on their impact to the seismic risks of hospital facilities.

Acknowledgments

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