Probabilistic Engineering Mechanics 25 (2010) 235–244

Contents lists available at ScienceDirect

Probabilistic Engineering Mechanics

journal homepage: www.elsevier.com/locate/probengmech

Enhancement of seismic sustainability of critical facilities through system analysis

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A R T I C L E I N F O

Article history:
Received 20 February 2009
Received in revised form
11 December 2009
Accepted 20 December 2009
Available online 4 January 2010

Keywords:
Critical facilities
Retrofit prioritization
System analysis
Seismic response
Fragility curves
Nonstructural components

A B S T R A C T

Proper functioning of critical facilities such as acute care hospitals and fire stations are essential in the aftermath of a severe earthquake. For these facilities to remain operational, not only their building structures must remain safe for continued occupancy, but also their nonstructural components/systems must remain functional. Motivated by a previous study by the second author, this paper demonstrates a probabilistic system analysis for enhancing the sustainability of deficient critical facilities. The analysis, in principle, utilizes event and fault tree procedures to evaluate the system fragility defined by the probability that the system will not perform its intended purpose. Enhancement of sustainability is demonstrated by using a representative numerical model of an existing facility. The study shows that by selecting the most vulnerable components, utilizing the concept of annual sensitivity index, the annual probability of failure can be reduced significantly in a cost-effective way.

1. Introduction

1.1. Background

In a severe earthquake event, critical facilities such as hospitals and fire stations must remain operational in order to assist seismically injured and otherwise traumatized people with immediate medical care and to lead the emergency response. For hospitals, since the evacuation of seriously ill patients may be very difficult, their proper functioning in the aftermath of a seismic event is of utmost important. Furthermore, replacing or repairing heavily damage critical facilities may take decades. For example, several hospitals in the Los Angeles area were nonfunctional even a decade after the 1994 Northridge earthquake and, thus, deprived service to the regional communities. For such facilities to remain operational, not only their building structures must remain safe for continued occupancy, but also their nonstructural components must function properly. For typical acute care hospitals, these nonstructural components include elevators, stairs, HVAC systems, water systems for usable water and fire suppression, communications and utility systems, electric power systems as well as a variety of medical equipment for life support, laboratory testing, operations and other primary and secondary needs for patient care.

According to a 2005 report from the office of statewide health planning and development of California [1], in the state of California, there are (i) 973 buildings (approximately 33% of the state's hospital buildings) that may collapse or pose life-safety threats and (ii) 175 hospital buildings that do not pose life-safety threats but may not be functional in the aftermath of a strong earthquake event. To improve their performance, acute care hospitals and facilities, in general, are required to conform to the California Law SB 1953 (California Senate Bill 1953, an amendment to the Alfred E. Alquist Hospital Seismic Safety Act of 1983). Thus, in the case of a severe earthquake event, all those buildings that pose life-safety threats or functionality problems have to be replaced, retrofitted or removed within the prescribed time line following the Alquist Act.

Significant studies have been made to seismically upgrade and retrofit the structures and nonstructural components in critical facilities. Indeed, developments following the 1971 San Fernando earthquake in the seismic design and construction of buildings have been proved to be significant. The Olive View Hospital building, which was damaged severely by the San Fernando earthquake and rebuilt conforming to the California's Hospital Act, did perform structure-wise excellently under the 1994 Northridge earthquake. Unfortunately, however, the hospital suffered from seismically induced physical failures and other functional impairment of its nonstructural components so severely that 377 patients had to be evacuated on the occasion of the Northridge earthquake. For nonstructural components, there are no definitive codes, regulations and guidelines developed as

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doi:10.1016/j.probengmech.2009.12.002

yet that can take into consideration the design, manufacturing, qualification test, installment, operation and maintenance from a system performance point of view. A number of studies separately dealt with some of these issues without significantly recognizing the systems aspect. However, the importance of the seismic performance of nonstructural components from a systems point of view has been highlighted in recent studies, (e.g., [2–4]). In fact, a paper by Bruneau and Reinhorn [4] presents an interesting and detailed approach in this context. Without such recognition of system aspects, codes and guidelines may be developed for each type of nonstructural components, as often observed so far, implicitly allowing them to be designed at a specific risk level of seismically induced failure or malfunction. The problem is that the risk level thus assigned, though implicitly, may not be consistent with the importance of the function this type of components provide, when looked at from the systems point of view.

1.2. System analysis

The concept and applications of seismic system risk analysis for critical structures or infrastructure systems have been evolving for many years. The Nuclear Regulatory Commission uses probabilistic seismic risk assessment for nuclear power plants. Recently, many studies (e.g., [5–11]) have used probabilistic seismic risk assessments for lifeline systems. The probabilistic approach permits the introduction of the uncertainty and randomness involved in the analytical models and the earthquake phenomena into the analysis in a rational fashion. The system analysis takes into consideration component fragilities and, in principle, utilizes the event and fault tree procedures to evaluate the system fragility defined by the probability that the system will not perform its intended purpose.

The major effort in the initial systems analysis is to acquire as much fragility information as possible for each component of a system. Fragility information can be based on experimental results, numerical simulation and experience data. Recently, utilizing dynamic shaking table test results, fragility curves for many nonstructural components have been developed (see, for example, [12–16]). In the absence of component fragility curves, static and dynamic test data can be used for estimating the fragility parameters. When the component's mechanical characteristics can be analytically modeled, not only static but also dynamic analysis can be performed for the purpose of acquiring fragility information. If, however, the component is mechanically complex and its loss of functionality can not be properly predicted by numerical simulations, engineering judgments coupled with past experience must be exercised for arriving at reasonable fragility information in the absence of proper test data.

1.3. Development of logic trees

Two types of logic trees are usually considered in the systems analysis; fault trees and event trees. The fault trees schematically depict the components and their functional interrelationship. A basic combination of components consists of a tree like relationship, where the component on top is related to its contributing components either by an 'and' gate or by an 'or' gate (logic gates). An 'and' gate means that the top component is functional if all the contributing components are functional, whereas an 'or' gate indicates that the top component is functional if at least one of the contributing components is functional. Each component can in turn have their own contributing components. This process of breaking down a component continues until it reaches the basic components representing individual pieces of equipment.

The event trees provide a logical sequence in which significant events will occur leading to specific consequences with their occurrence probabilities. In the limited scope of this study, the consequence of interest is the annual probability of the system remaining functional or becoming nonfunctional immediately after an earthquake. Because of this, the event tree analysis is not performed in this study explicitly. Failures of two systems/components (such as the in-house water and electric power systems) are not necessarily independent, however, due to their potential consequential interactions. The examination of such dependency can only be carried out logically with the aid of the event tree analysis, and is an interesting and important future study.

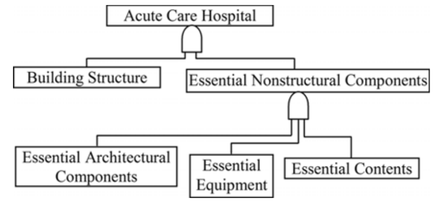

Fig. 1. Fault tree of a typical acute care hospital.

Fig. 1 shows the fault tree for a typical acute care hospital. Note, for proper functioning of a hospital, both building and the essential nonstructural components must function. The essential nonstructural components include essential architectural components (such as suspended ceilings and partition walls), mechanical, electrical and medical equipment and systems, and building contents (e.g., chemical glassware, desktop computers and monitors). In a typical hospital building, there are numerous nonstructural components with varying dynamic properties and functionality. In order to focus the attention to demonstrate system performance issues at a manageable level of completeness, this study (1) assumes that the hospital building structure itself must remain safe for continued occupancy and patient care after a damaging earthquake and (2) is limited to only a few critical components and systems, which are identified during recent earthquakes to be most vulnerable, i.e., in-house water and electric power systems, HVAC, suspended ceilings, and medical monitors [17]. Note that apart from proper functioning of the structure and nonstructural components, other potential impacts of earthquakes, such as the decreased availability of medical and administrative staff at the hospital, reduced number of usable ambulances, and curtailed accessibility to the hospital by ambulances and other vehicles due to the seismic damage to surface transportation systems that are important for a hospital in terms of providing service to a community, are not considered here.

1.4. Scope of this paper

The present study explores the systems aspect focusing on typical acute care hospitals and hence, demonstrates systems analysis for the purpose of the development of a framework for design codes and guidelines for enhancing sustainability of critical facilities. The study is an enhancement of a previous research by Shinozuka [3] for the FEMA/USC (Federal Emergency Management Agency/ University of Southern California) project. First, a few essential components from the systems point of view are identified based on a recent earthquake damage survey and their fragility information is collected. In addition, the fragility of the hospital building is also evaluated. Fault trees are utilized for the in-house water and electric power systems. A system fragility curve is then developed for maintaining operation of the hospital in the aftermath of a strong earthquake, based on the fault tree of the hospital function. The system analysis is then performed to estimate the annual probabilities of system failure for each constituting component or system that is required for the hospital's operation. These probabilities are assessed for general acceptability of system performance and compared to each other from the risk consistency point of view. Next, sensitivity analysis