APPLICATION OF MCEER FRAGILITY-BASED DECISION SUPPORT METHODOLOGY TO A BENCHMARK HOSPITAL

C. Kafali[1], M. Grigoriu[2] and G.P. Cimellaro[3]

[1] *Research Engineer, AIR Worldwide Corporation, Boston, MA, USA*
[2] *Professor, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY, USA*
[3] *Postdoctoral Research Associate, Dept. of Civil Engineering, University at Buffalo, Buffalo, NY, USA*

Email: ckafali@air-worldwide.com, mdg12@cornell.edu, gpc2@buffalo.edu

ABSTRACT :

A methodology is presented for calculating the seismic performance of structural/nonstructural systems in a health care facility and developing rational strategies for increasing the seismic resilience of these systems. The methodology is based on (*i*) seismic hazard analysis, (*ii*) fragility analysis and (*iii*) life-cycle capacity and cost estimation. Systems seismic performance is measured by fragility surfaces, that is, the probability of system failure as a function of moment magnitude and site-to-source distance of a seismic event, consequences of system damage and failure, and system recovery time following seismic events. The input to the analysis consists of site seismic hazard, structural/nonstructural systems properties, performance criteria, rehabilitation strategies, and a reference time. Estimates of losses and recovery times, referred to as life-cycle losses and recovery times, can be derived using fragility information, financial models, and available resources. MCEER West Coast Demonstration Hospital is used to demonstrate the method. The seismic risk of the MCEER Hospital is assessed based on the performance of its structural system and three nonstructural systems attached to the structural system at different locations, namely, the Heat-Ventilation-Air-Conditioning system, piping system and partition walls. Fragilities are obtained for the structural and nonstructural systems for several limit states. Also, statistics are obtained for life-cycle losses and recovery times corresponding to different rehabilitation strategies and an optimal rehabilitation strategy is selected using these statistics.

KEYWORDS: fragility, life-cycle loss estimation, resilience measures, seismic hazard

1. INTRODUCTION

Capital allocation decisions for a health care facility include, for example, opening a new unit, extending or closing some existing units, buying new equipment, and relocating the hospital building. These decisions are based on life-cycle capacity, viewed as the level of performance defined for a service, and cost estimates. Existing geotechnical, structural/nonstructural systems can be left as they are or can be retrofitted using one of the available rehabilitation alternatives. Leaving a system as it is can be reasonable for short-term decisions but retrofitting the system, despite its initial costs, might be beneficial in the long run. A probabilistic methodology is required to make a rehabilitation decision since seismic hazard and system performance are uncertain.

This study presents a methodology for (1) evaluating the seismic performance of an individual health care facility during a specified time interval, and (2) selecting an optimal rehabilitation strategy for this facility from a collection of different rehabilitation strategies. Figure 1 shows a chart illustrating the principal elements of the fragility-based capital allocation decision support system used in this paper. The seismic performance is measured by fragility surfaces, that is, the probability that a system response exceeds a critical value, defining a damage-level, as a function of moment magnitude and site-to-source distance of a seismic event. The input to the analysis consists of site seismic hazard information, geotechnical and structural/nonstructural systems properties, performance criteria, rehabilitation strategies, and a reference time. Estimates of losses and recovery times, referred to as life-cycle losses and recovery times, can be derived using fragility information and financial models. Life-cycle costs consist of (1) initial costs related to the rehabilitation of the system, (2) repair/replacement costs for bringing the damaged systems back to their original states, (3) cost of life, and (4) indirect costs related to the loss of capacity of the hospital.

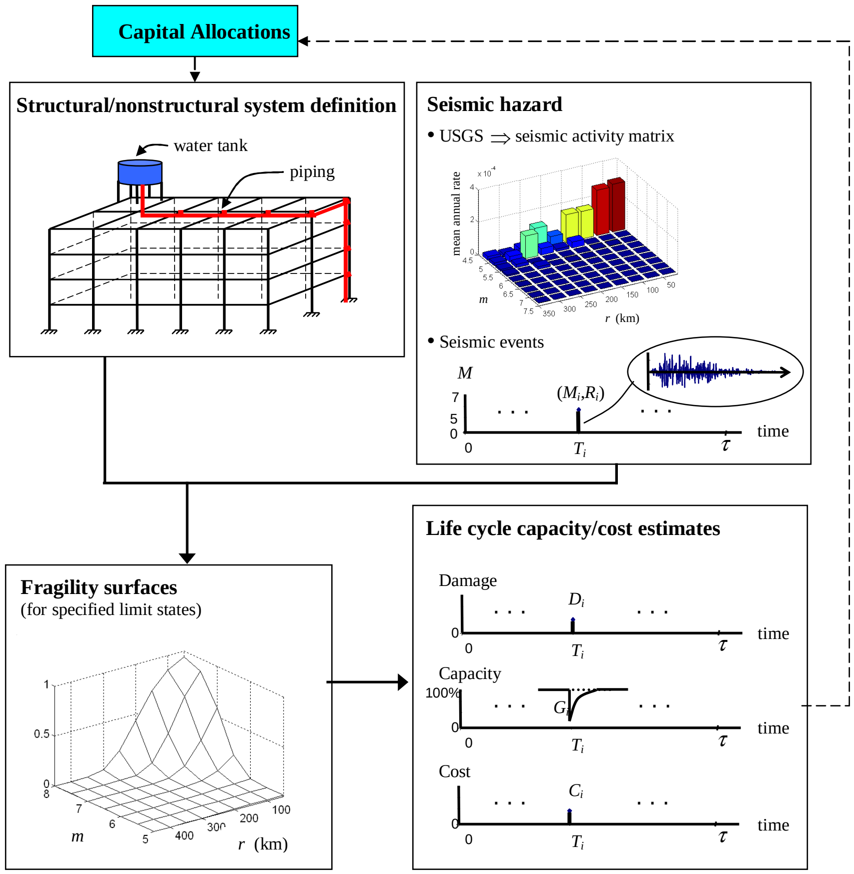

Figure 1 Principal elements of the MCEER fragility-based decision support methodology

MCEER West Coast Demonstration Hospital, from this point forward referred to as MCEER Hospital, is used to demonstrate the method. The seismic risk of the MCEER Hospital is assessed based on the performance of its structural system and three nonstructural systems attached to the structural systems at different locations, namely, the Heat-Ventilation-Air Conditioning (HVAC) system consisting of two water chillers, piping system and partition walls. Monte Carlo simulation is used for obtaining statistics of the life-cycle losses and recovery times corresponding to different rehabilitation strategies and an optimal rehabilitation strategy is selected using these statistics.

2. LOSS ESTIMATION METHOD

The method is based on (*i*) Monte Carlo simulation, (*ii*) seismic hazard analysis, (*iii*) fragility analysis and (*iv*) life-cycle capacity and cost estimation. The method (1) considers a realistic seismic hazard model rather than using the maximum credible earthquake, (2) includes all components of costs, that is, the costs related to the structural failure and downtime, retrofitting, repair, loss of capacity in services, and loss of life, and (3) is designed for individual facilities rather than a large population of them. The probabilistic seismic hazard models presented in (Kafali and Grigoriu, 2008, Sections 1 and 2) are used to characterize (1) the moment magnitude M_i, source-to-site distance R_i and the arrival time T_i of the seismic event i, (2) the ground accelerations at the system site resulting from the seismic event i defined by (M_i,R_i), and (3) the total number of seismic events $N(\tau)$ in lifetime τ. Specific barrier model (Halldorsson and Papageorgiou, 2005) is used to define the seismic hazard at a given site following an earthquake with moment magnitude m and source-to-site distance r. Accordingly, the probability law of the site seismic hazard is completely defined by (m,r) and the soil condition at the site.

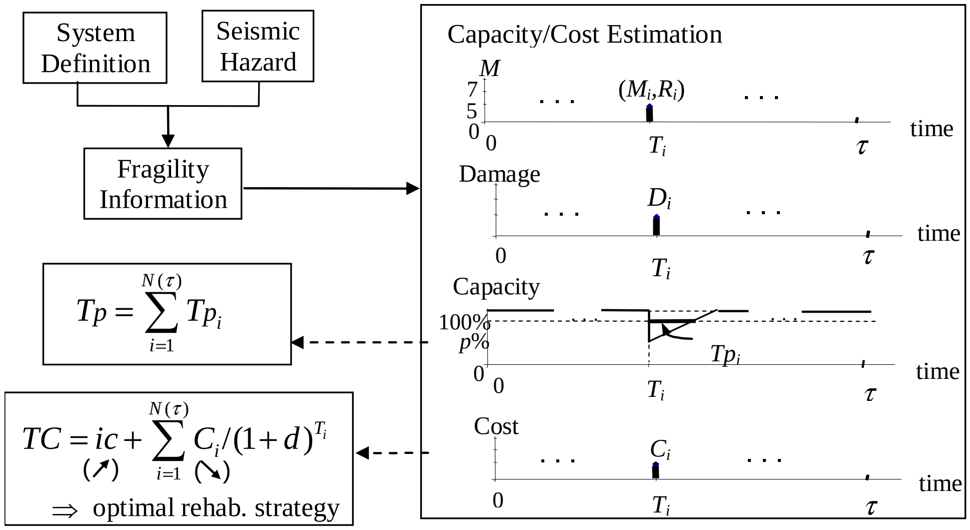

Figure 2 Loss estimation method

The United States Geological Survey provides realizable values of (m,r) at each zip code in the United States, and mean yearly rates, ν_{ij} of earthquakes with moment magnitude m_i and source-to-site distance r_j (USGS, 2006); see, for example, Fig. 3 for Northridge, California. Given that an earthquake occurs at a site, the probability that it has parameters (m_i,r_j) is ν_{ij}/ν, where $\nu=\Sigma_i\Sigma_j\nu_{ij}$. The seismic fragility analysis presented in (Kafali and Grigoriu, 2007; Kafali and Grigoriu, 2008, Section 3.3) is used to characterize the damage in the structural/nonstructural systems. For example, let D_i be a discrete random variable characterizing the damage state of a nonstructural system after seismic event i with moment magnitude m_i and source-to-site distance r_i, $i=1,\ldots, N(\tau)$. Assume that a nonstructural system enters damage state d_k, with probability $p_{k,i}$ for $k=1,\ldots,n$, where n is the number of damage states. The probabilities $p_{k,i}$ can be obtained from the fragility information of the nonstructural system and are functions of the limit state defining the damage state d_k and (m_i,r_i). Similarly, we can define random variables characterizing the damage in the structural system and components of the selected nonstructural systems.

In Fig. 2 Tp is the total time the system operates below p% capacity in τ, Tp_i is the time the system operates below p% capacity after event i and TC is the total cost in τ in present value, in which ic is the initial cost related to the rehabilitation, d is the discount rate, and C_i is the cost related to event i including costs of repair/replacement, capacity losses and life losses due to the damage in structural and nonstructural systems. It is expected that with an increasing initial cost ic, the cost C_i due to event i will decrease and for some rehabilitation alternative we will have the optimum solution. The numerical results in the following sections are for p=90 and d=0.05.

The resilience metrics, that is, the decision variables used for selecting the optimal rehabilitation alternative are the total time Tp the system operates below p% capacity, and the total cost TC in τ, defined in Fig. 2. Estimates of the distributions of Tp and TC can be obtained using Monte Carlo simulation. First, a seismic hazard sample at the site during lifetime τ is generated using the Monte Carlo algorithms developed in (Kafali and Grigoriu, 2008, Section 2.4). A seismic hazard sample is defined by the number of earthquakes during the time τ, and magnitude and source-to-site distance and arrival time of each of them. For each event in the seismic hazard sample damage states of structural/nonstructural systems are simulated from their fragility information, and corresponding capacity losses and costs are calculated. The total time the system operates below p% capacity and the total cost in $[0,\tau]$ corresponding to the seismic hazard sample are obtained by adding contributions from each event in the seismic hazard sample, that is, using the equations for Tp and TC shown in Fig. 2. Repeating the above analysis for n_s independent samples, we obtain n_s samples of Tp and TC. Hence histograms and other statistics of Tp and TC depending on user's objectives can be calculated from these samples.

3. NUMERICAL EXAMPLE

Following is a brief summary of the example presented in detail in (Kafali and Grigoriu, 2008, Section 4.1).

3.1. Seismic Hazard Information and Dynamic Analysis

The MCEER Hospital is in Northridge, California. The lifetime is set to τ =50 years. Figure 3 shows the seismic activity matrix at the system site, providing the mean annual arrival rate of earthquakes with different moment magnitude *m*, and source-to-site distance *r*, for which ν =0.95.

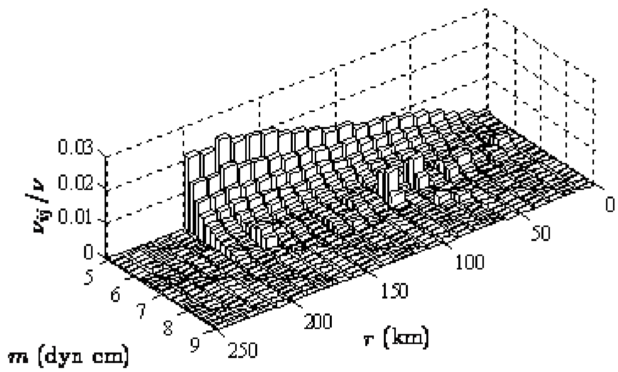

Figure 3 Seismic activity in Northridge, California

The hospital is located on stiff soil (NEHRP site class D, (FEMA-273, 1997)). The cascade approach, that is, the nonstructural system does not affect the dynamics of the supporting structure, is used for the dynamic analysis of the structural and nonstructural systems. The stationary response to strong ground motion is used in seismic performance analysis. Methods based on crossing theory of stochastic processes presented in (Kafali and Grigoriu, 2008, Section 3.3.1) are used for calculating fragility surfaces for structural/nonstructural linear systems subjected Gaussian seismic ground accelerations. It is assumed that all the systems are brought to their original states after each seismic event.

3.2. Structural System

The MCEER Hospital is an inpatient facility in the Northridge Hospital Medical Center. The four-storey facility was constructed in the early 1970's to meet the seismic requirements of the 1970 Uniform Building Code. There are 93 beds in the facility and the net revenue per bed per day (per patient day) is $1,500. A one-dimensional equivalent linear version of a two-dimensional inelastic model of the MCEER Hospital is used in this study for seismic risk analysis. Accordingly, the structure is modeled by a 4-degree-of-freedom shear beam model with a classical damping matrix. Three alternative designs, with the same stiffness as the existing system but with increased levels of damping are considered. The alternative designs are obtained by adding linear viscous dampers inserted in the central bay in each storey of the exterior moment-resisting frame of the original MCEER Hospital model. Associated rehabilitation costs were calculated.

Maximum inter-storey drift is used to assess the structural performance. Four damage states, namely, immediate occupancy, life safety, collapse prevention and collapse, are defined using (FEMA-356, 2000). Fragilities are calculated from the (*i*) model, (*ii*) response and (*iii*) damage states. Figure 4 shows the probability that the maximum inter-storey displacement ratio exceeds 2.5% (that is, the life safety limit state) for (a) the base system and (b) the rehabilitation alternative 3 (with the highest amount of damping). As expected, system fragility gets smaller from (a) to (b) as more damping is added to the system. Associated repair/replacement costs, disruption of service for these damage states and corresponding capacity losses are calculated. Life losses in case of total collapse is also modeled and incorporated in the loss estimation.

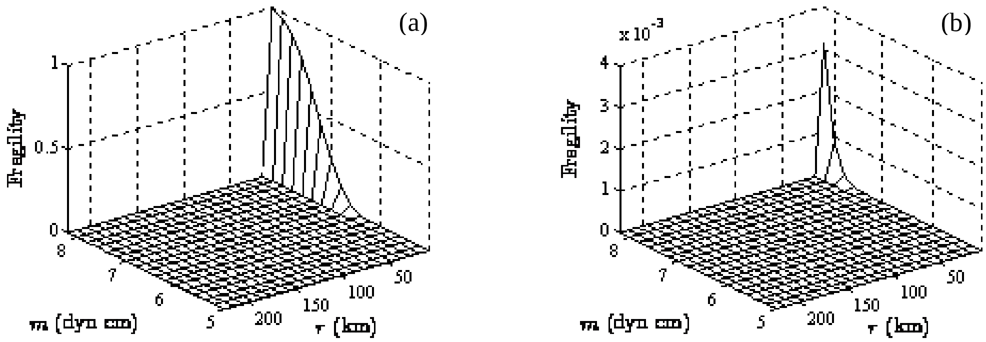

Figure 4 Example structural system fragilities: (a) base system, (b) rehabilitation alternative 3

3.3. Nonstructural Systems

The seismic performances of three nonstructural systems, HVAC system, partition walls and piping system, are examined. It is assumed that the nonstructural systems are not interacting, that is, the responses of these systems are independent of each other.

It is assumed that the HVAC system consists of two identical water chillers attached to the roof of the building. A three dimensional nonlinear model of the HVAC equipment (Fathali and Filiatrault, 2007), which delivers relative acceleration response of the center of mass of the HVAC equipment in the longitudinal, transverse and vertical directions, is used. The response in only the transverse (short) direction of HVAC is considered the for seismic performance analysis. No rehabilitation is used for the HVAC system. HVAC equipment is an acceleration sensitive nonstructural system. The damage and limit states are defined using (ASHRAE, 2003). Fragilities are calculated from the (*i*) model, (*ii*) structural response (excitation at attachment points) and (*iii*) damage states. Associated repair/replacement costs, disruption of service for these damage states and corresponding capacity losses are calculated.

The number of partition walls in each floor of the MCEER Hospital is estimated using its architectural drawings. It is assumed that the partition walls in the MCEER Hospital are of the types reported in (McMullin and Merrick, 2002); in which partition wall damage was given as a function of the inter-storey drift. Hence no wall model is required for fragility analysis and loss estimation. No rehabilitation is used for the partition walls. Fragility information provided in (McMullin and Merrick, 2002) is used to define partition wall damage/limit states. Fragilities surfaces are calculated from the structural system response (inter-storey drift) and damage states. Associated repair/replacement costs, disruption of service for these damage states and corresponding capacity losses are calculated.

It is assumed that the piping system tested at University of Nevada at Reno (Corbin, 2006; and Goodwin and Maragakis, 2007) can be used to describe limit/damage states of the existing piping system at the MCEER Hospital. The experimental results were acquired for a steel/threaded piping system with unbraced and braced alternatives. The number of different elements in the sanitary piping system at each floor of the MCEER Hospital is estimated using its architectural drawings and considering only the pipes with diameter greater than or equal to one inch. The number of hangers is estimated assuming a spacing of 10 feet. Piping system damage is assumed to be a function of the inter-storey drift. Hence, no pipe model is required for fragility analysis and loss estimation. The unbraced system is considered as the existing system. The braced system is used as the rehabilitation alternative. It is assumed that the pipes are braced at every second hanger location with a clevis support and bracing cables. Cost associated with this bracing option is estimated and is used as the cost of rehabilitation for the piping system. The damage/limit states are obtained from (Corbin, 2006). Fragilities are calculated from the structural system response (inter-storey drift) and the damage states. Associated repair/replacement costs, disruption of service for these damage states and corresponding capacity losses are calculated.

Figure 5 shows example fragility surfaces for the nonstructural systems attached the structural system with no rehabilitation. In Fig. 5, panel-a shows the probability that the maximum acceleration response of the HVAC equipment exceeds 2.0*g* (HVAC equipment has at least moderate damage), panel-b shows the probability that a partition wall located on the 1st floor has extensive damage or completely failed and panel-c shows the probability that existing (unbraced) piping system located on the 1st floor has extensive damage.

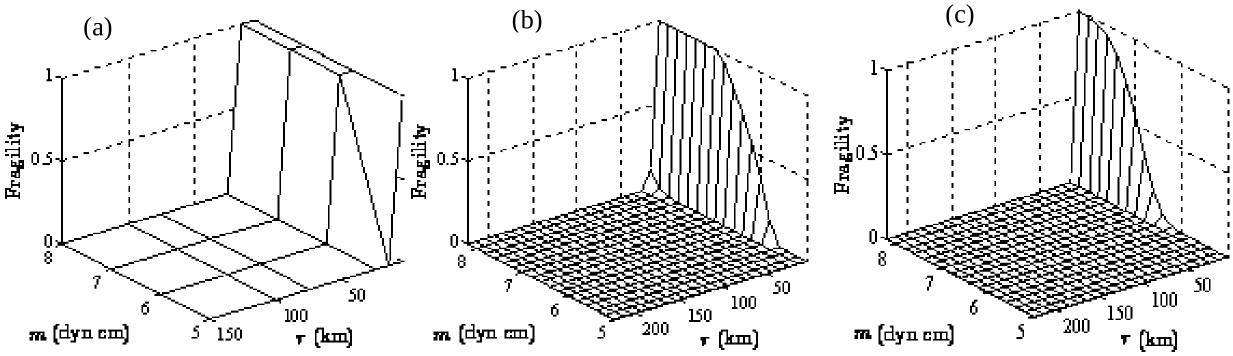

Figure 5 Example nonstructural system fragilities: (a) HVAC, (b) partition wall, (c) piping system

3.4. Loss Estimation Algorithm and the RDAT

The Monte Carlo based algorithm for calculating the decision variables (1) the total time *Tp* the system operates below *p*% capacity, and (2) the total cost *TC*, in τ, which are used for selecting the optimal rehabilitation alternative is outlined in Fig. 6.

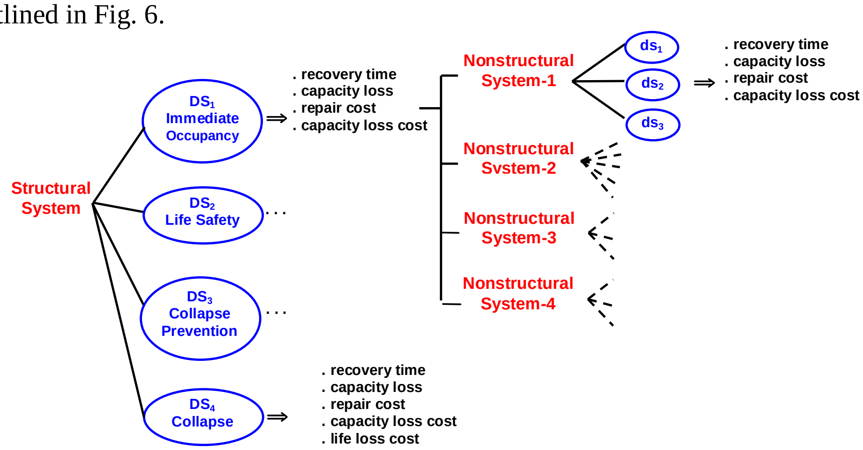

Figure 6 Monte Carlo algorithm for loss estimation

First, for a given event in a lifetime seismic hazard sample damage state probabilities for the structural and nonstructural systems are obtained from their corresponding fragility surfaces. We then generate samples of damage states for the structural/nonstructural systems. Next, recovery time and total event cost (consisting of repair, replacement, capacity loss and life losses due to structural/nonstructural damage) for this event, are obtained from the available consequence/financial information. Recovery times and total event costs from all events in a hazard sample are added to obtain a sample of *Tp* and *TC*. The probability laws of *Tp* and *TC* are estimated by generating many samples of lifetime seismic hazards and obtaining corresponding values for *Tp* and *TC*.

The algorithm in Fig. 6 is implemented in Rehabilitation Decision Analysis Toolbox (RDAT), a MATLAB based program for calculating the seismic resilience of structural/nonstructural systems in a health care facility (RDATv1, 2004; Kafali and Grigoriu, 2005).

3.5. Results

Figure 7 (a) and (b) show the marginal probability density functions of the (a) total time *Tp* the system operates below *p*=90% capacity, and (b) total cost TC in τ= 50 years, for the base system and the three rehabilitation alternatives, calculated by Monte Carlo simulation using 1,000 samples.

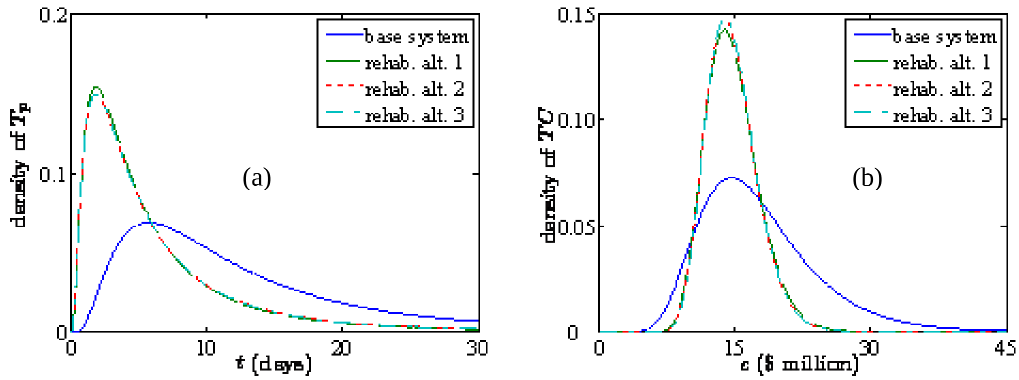

Figure 7 Probability density functions of (a) *Tp* and (b) *TC*

Figure 8 (a) and (b) show *P*(*Tp*>*t*) and *P*(*TC*>*c*). A possible measure for comparing the effectiveness of different rehabilitation alternatives can be the probability that the total time *Tp* the system operates below 90% capacity exceeds a level t_{cr} (or similarly, the probability that the total cost *TC* exceeds a level c_{cr}). Accordingly,

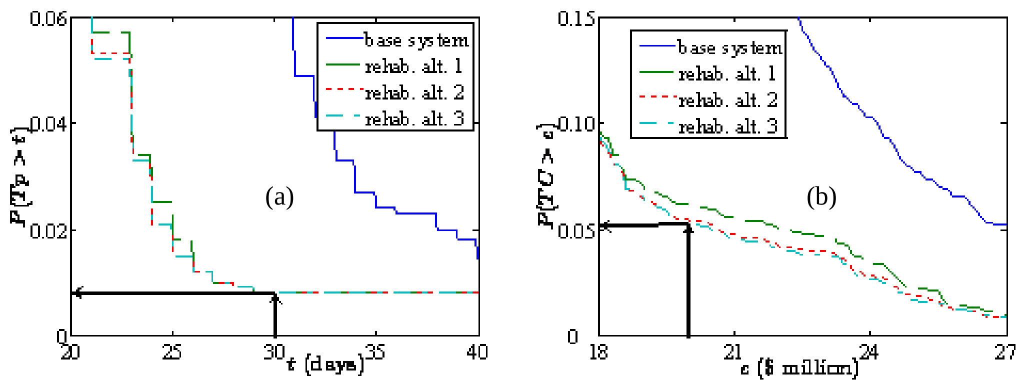

Figure 8 Decision based on (a) *Tp* or (b) *TC*

the optimal solution is the one with the lowest $P(Tp > t_{cr})$ (or $P(TC > c_{cr})$) and depends on the selected value of t_{cr} (or c_{cr}). For example, Fig. 9 (a) shows that the optimal solutions are rehabilitation alternatives 1, 2 and 3 for t_{cr} = 30 days, or Fig. 9 (b) shows that the optimal solution is the rehabilitation alternative 3 for c_{cr} = \$20 million. If both *Tp* and *TC* are considered for selecting an optimal solution, then the alternative resulting in the highest $P(Tp<t_{cr}, TC<c_{cr})$ is the optimal solution. For t_{cr} = 30 days and c_{cr} = \$20 million, the optimal solution is the rehabilitation alternative 3.

4. CONCLUSIONS

The presented loss estimation method was implemented in computer programs and the life-cycle risk analysis methodology was illustrated through numerical examples. MCEER West Coast Demonstration Hospital was analyzed to identify an optimal rehabilitation strategy with respect to total life-cycle losses using the concepts of seismic activity matrix and fragility surfaces. It was shown that proposed retrofitting alternatives do not change the mean value of the life-cycle costs significantly; however, the probability of exceeding large costs was lower for the retrofitted systems.

The presented loss estimation method can be immediately extended to systems under multihazard environment. For example, in the case of two independent intermittent hazards, such as seismic and hurricane hazards at a site, the lifetime hazard sample may include three types of events, two individual hazard events and one coincidental hazard event. For the individual hazard events presented method can be directly applied provided that the fragility information of the system for these hazards are readily available. For the coincidental hazard event system fragility under the combined hazards is required. Once the system fragility is calculated lifetime loss estimation can be performed following the presented algorithm.

ACKNOWLEDGEMENTS

This work was supported primarily by the Earthquake Engineering Research Center Program of the National Science Foundation under NSF Award Number EEC-9701471 to the Multidisciplinary Center for Earthquake Engineering Research. This support is gratefully acknowledged. We would like to also acknowledge A. Bansal, F. Case, Dr. A. Filiatrault, J. Lewis, R.J. Love, Dr. M. Maragakis, P. Marks, J. Massey, J. Mitchell, R. Omens, R. Rozanski, A. Taylor, D.P. Taylor and Dr. D. von Winterfeldt for their contributions and critical reviews.

REFERENCES

ASHRAE. (2003). ASHRAE Handbook: HVAC Applications. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, GA. (Chapter 34, Thermal Storage).

Corbin, R.C. (2006). Experimental Evaluation of the Seismic Performance of Hospital Copper Piping Systems. MS. Thesis. University of Nevada, Reno.

Fathali, S. and Filiatrault, A. (2007). Experimental Seismic-Performance Evaluation of Isolation/Restraint Systems for Mechanical Equipment; Part I: Heavy Equipment Study. Technical Report, MCEER-07-0007. Multidisciplinary Center for Earthquake Engineering Research. Buffalo, NY.

FEMA-273. (1997). NEHRP Guidelines for the Seismic Rehabilitation of Buildings. Technical Report, FEMA Report 273, Federal Emergency Management Agency. Washington, DC.

FEMA-356. (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Technical Report, FEMA Report 356, Federal Emergency Management Agency. Washington, DC.

Goodwin, E.R. and Maragakis, E.M. (2007). Experimental Evaluation of the Seismic Performance of Hospital Piping Subassemblies. Technical Report, MCEER-07-0013. Multidisciplinary Center for Earthquake Engineering Research.

Halldorsson, B. and Papageorgiou, A.S. (2005). Calibration of the Specific Barrier Model to Earthquakes of Different Tectonic Regions. *Bulletin of the Seismological Society of America*, **95:4**, 1276–1300.

Kafali, C. and Grigoriu, M. (2008). System Performance Under Multi-Hazard Environments. Technical Report, MCEER-08-0006. Multidisciplinary Center for Earthquake Engineering Research. Buffalo, NY.

Kafali, C. and Grigoriu, M. (2007). Seismic Fragility Analysis: Application to Simple Linear and Nonlinear Systems. *Earthquake Engineering and Structural Dynamics*, **36:13**, 1885-1900.

Kafali, C. and Grigoriu, M. (2005) Rehabilitation Decision Analysis Toolbox. Proceedings of the Convention of Structural Engineers Association of California (SEAOC). San Diego, CA.

McMullin, K.M. and Merrick, D. (2002). Seismic Performance of Gypsum Walls - Experimental Test Program. Technical Report, CUREE Woodframe Project Report W-15. Consortium of Universities for Research in Earthquake Engineering. Richmond, CA.

RDATv1. (2004). Rehabilitation Decision Analysis Toolbox (RDAT) Version 1, Software Tool and User Manual. MCEER Users Network. Multidisciplinary Center for Earthquake Engineering Research. Buffalo, NY.
URL: *http://civil.eng.buffalo.edu/users_ntwk/computational/platforms/DecisionAnalysisToolboxV1/index.html*.

USGS. (2006). National Seismic Hazard Mapping Project, Earthquake Probability Mapping. United States Geological Surveys. URL: *http://eqint.cr.usgs.gov/eq-men/html/neweqprob-06.html*