

# Application of Fragility-Based Decision Support Methodologies

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## Summary

A method is presented for assessing the seismic performance of acute care facilities and selecting optimal rehabilitation strategies for increasing the seismic resilience of these facilities. The seismic performance is measured by fragility surfaces, that is, the probability of system failure as a function of magnitude and site-to-source distance, consequences of system damage/failure, and system recovery time following earthquakes. The input to the analysis consists of system properties, seismic hazard, performance criteria, rehabilitation strategies, and a lifetime. MCEER West Coast Demonstration Hospital is used to demonstrate the method. Statistics are obtained for lifetime losses and recovery times corresponding to different rehabilitation strategies and an optimal rehabilitation strategy is selected using these statistics.

## Loss Estimation Method

The proposed method is based on (i) seismic hazard analysis, (ii) fragility analysis and (iii) lifetime capacity/cost estimation (Kafali and Grigoriu 2005a). Figure 1 shows a chart summarizing the method.

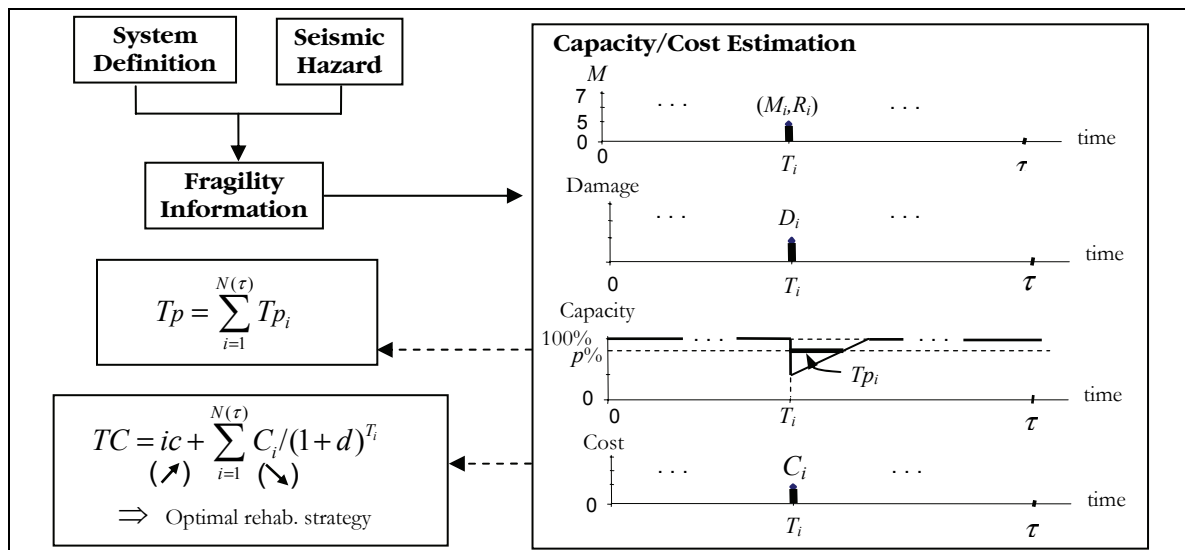


Figure 1. Loss estimation method.

In Figure 1,  $T_i$  is the arrival time of the seismic event  $i$  with moment magnitude  $M_i$  and source-to-site distance  $R_i$ ,  $\tau$  is the lifetime,  $N(\tau)$  is the total number of seismic events in  $\tau$ ,  $T_{p_i}$  is the time the system operates below  $p\%$  capacity after event  $i$ ,  $T_p$  is the total time the system operates below  $p\%$  capacity in  $\tau$ ,  $ic$  is the rehabilitation cost,  $C_i$  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,  $TC$  is the total cost in  $\tau$  and  $d$  is the discount rate. More information can be found in (Kafali and Grigoriu 2005a).

## System Definition

A simple 2 dimensional model is used for representing the structural system of the MCEER West Coast Demonstration Hospital. More information on the model is in (Kafali and Grigoriu 2006a). Three nonstructural systems are considered in this study.

- HVAC system: It is assumed that the HVAC system consisted of two identical water chillers attached to the roof of the building. Response of these chillers to the roof accelerations are obtained using a 3 dimensional nonlinear model presented in Fathali and Filiatrault (2006).
- Piping system: The topology and the components of the sanitary water supply system are obtained using the architectural drawings of the demonstration hospital (see Table 1). Only the pipes with a diameter greater than or equal to one inch are considered.
- Partition walls: The topology of the partition wall system is obtained using the architectural drawings of the demonstration hospital (see Table 2). It is assumed that all the walls between the rooms and between the rooms and the corridors are of the same type.

**Table 1. Piping system.**

Floor	Length [ft]	Connections	Valves	Hangers
<b>1</b>	330	45	15	33
<b>2</b>	510	115	40	51
<b>3</b>	510	115	40	51
<b>4</b>	270	60	25	27

**Table 2. Partition walls.**

Floor	Walls	Effectuated # of beds						
		0	1	2	3	4	5	6
<b>1</b>	80	80	0	0	0	0	0	0
<b>2</b>	80	33	14	18	7	6	1	1
<b>3</b>	60	20	2	28	2	8	0	0
<b>4</b>	80	80	0	0	0	0	0	0

It is assumed that (i) cascade analysis applies, *i.e.*, the nonstructural systems do not affect the dynamics of the structural system, and (ii) systems are brought to their initial state after each event.

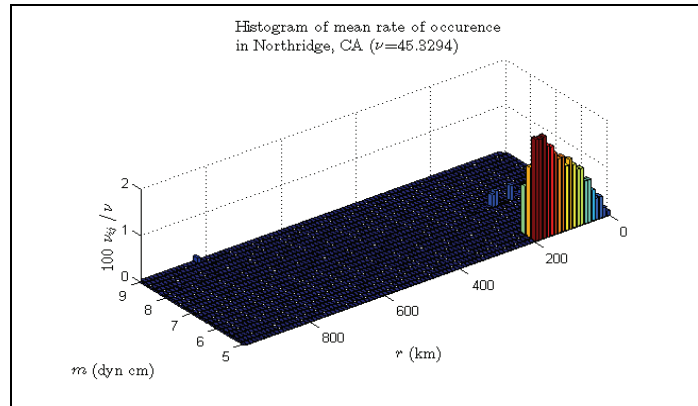
## Rehabilitation alternatives:

- Structural system: Three alternative designs, with (i) the same stiffness as the existing system and (ii) linear viscous dampers resulting in the first mode damping ratios of 20, 25 and 30%, for the alternatives 1, 2 and 3, respectively, are considered. The dampers are inserted in the central bay in each storey of the exterior moment-resisting frame. The total rehabilitation costs for the alternatives 1, 2 and 3 are \$109,000; \$133,000 and \$180,000, respectively (Kafali and Grigoriu 2006a).

- Nonstructural systems: Rehabilitation is applied to the piping system only using bracing the system at each hanger location. The total cost of piping rehabilitation is \$120,000 (Kafali and Grigoriu 2006a).

## Seismic Hazard

The demonstration hospital is in Northridge, CA (118.52° West, 34.24° North) (Wanitkorkkul and Filiatrault 2005) and is located on stiff soil i.e., NEHRP site class D (FEMA 273 1997). The lifetime  $\tau$  is 50 years. Figure 2 shows the seismic activity matrix at the site, providing the mean annual rate of earthquakes with different  $(m,r)$ . The specific barrier model (Halldorsson and Papageorgiou 2005) is used to model the strong ground motion process at the site. A Monte Carlo algorithm can be developed for generating (i) random samples of the seismic hazard at the site during a given period of time  $\tau$  using the seismic activity matrix, and (ii) seismic ground acceleration samples for these seismic hazard samples. Each seismic hazard sample is defined by the number of earthquakes during the time  $\tau$ , temporal distribution, and magnitude and source-to-site distance of each of them. More information on seismic hazard analysis can be found in Kafali and Grigoriu (2003a, 2005a).



**Figure 2. Seismic activity matrix for Northridge, CA.**

## Fragility Information

Seismic fragility analysis of structural/nonstructural system is described in detail in Kafali and Grigoriu (2003b, 2006b). Table 3 shows the damage/limit states and sample fragility surfaces for the structural/nonstructural systems considered in this study. Damage states for the structural system, HVAC equipment, piping system and partition walls are provided in FEMA 356 (2000), ASHRAE (2003), Goodwin (2004), McMullin and Merrick (2002), respectively. More information on calculating the fragility surfaces for the systems in this benchmark problem can be found in Kafali and Grigoriu (2006a).

## Capacity/Cost Estimation

Capacity, for example acute care bed per day capacity, and total cost are estimated for the case of no rehabilitation and for the three rehabilitation alternatives. Using these estimates efficient solutions can be determined. The total capacity of the demonstration hospital is 93 acute care beds (43 on the 2<sup>nd</sup> floor and 50 on the 3<sup>rd</sup> floor). The net revenue per bed is \$1,500/day. The cost due to a seismic event relates to (i) structural/nonstructural repair or replacement, (ii) loss of capacity in services, and (iii) loss of life. Table 4 shows the repair/replacement costs and consequences corresponding to each damage state for the structural and nonstructural systems. It is assumed that there are 150 people in the hospital when an earthquake occurs, the probability that a person losses his/her life is 0.1 and the value of life \$2,200,000/person.

**Table 3. Damage/limit states and sample fragility surfaces for the structural/nonstructural systems.**

System	Damage states	Sample fragility surface														
Structure	<table border="1"> <thead> <tr> <th>Damage state</th> <th>Max story drift (%)</th> </tr> </thead> <tbody> <tr> <td>Immediate occupancy</td> <td>&lt; 0.7</td> </tr> <tr> <td>Life safety</td> <td>[0.7, 2.5)</td> </tr> <tr> <td>Collapse prevention</td> <td>[2.5, 5.0)</td> </tr> <tr> <td>Collapse</td> <td>≥ 5.0</td> </tr> </tbody> </table>	Damage state	Max story drift (%)	Immediate occupancy	< 0.7	Life safety	[0.7, 2.5)	Collapse prevention	[2.5, 5.0)	Collapse	≥ 5.0	<p>structure = no rehab, ds ≥ 3</p>				
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HVAC equipment	<table border="1"> <thead> <tr> <th>Damage state</th> <th>Max total acc. (g)</th> </tr> </thead> <tbody> <tr> <td>No</td> <td>&lt; 2.0</td> </tr> <tr> <td>Moderate</td> <td>[2.0, 4.0)</td> </tr> <tr> <td>Extensive</td> <td>≥ 4.0</td> </tr> </tbody> </table>	Damage state	Max total acc. (g)	No	< 2.0	Moderate	[2.0, 4.0)	Extensive	≥ 4.0	<p>structure = no rehab, ds ≥ 2</p>						
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Extensive	≥ 4.0															
Piping	<table border="1"> <thead> <tr> <th rowspan="2">Damage state</th> <th colspan="2">Max storey drift (%)</th> </tr> <tr> <th>Existing</th> <th>Rehab.</th> </tr> </thead> <tbody> <tr> <td>Slight</td> <td>&lt; 1.1</td> <td>&lt; 2.2</td> </tr> <tr> <td>Moderate</td> <td>[1.1, 2.2)</td> <td>[2.2, 5.0)</td> </tr> <tr> <td>Extensive</td> <td>≥ 2.2</td> <td>≥ 5.0</td> </tr> </tbody> </table>	Damage state	Max storey drift (%)		Existing	Rehab.	Slight	< 1.1	< 2.2	Moderate	[1.1, 2.2)	[2.2, 5.0)	Extensive	≥ 2.2	≥ 5.0	<p>structure = no rehab, ds ≥ 2</p> <p>(1st floor)</p>
Damage state	Max storey drift (%)															
	Existing	Rehab.														
Slight	< 1.1	< 2.2														
Moderate	[1.1, 2.2)	[2.2, 5.0)														
Extensive	≥ 2.2	≥ 5.0														
Partition wall		<p>structure = no rehab, ds ≥ 1</p> <p>(1st floor)</p>														

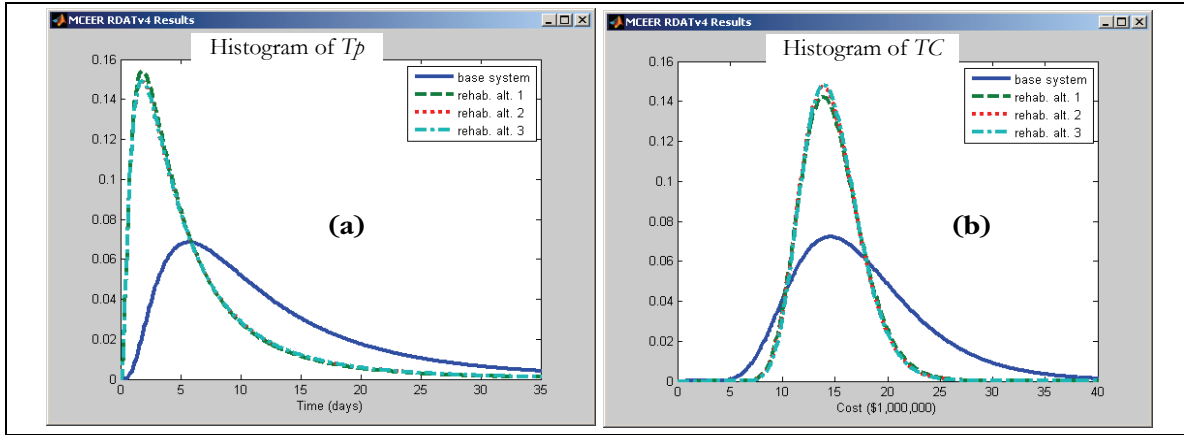
**Table 4. Repair/replacement costs and consequences due to damage in structural/nonstructural systems.**

System	Repair/replacement costs and consequences					
Structure	<b>Damage state</b>	<b>Repair/replacement cost</b>				<b>Consequences</b>
	Immediate occupancy	\$ 280,000				Hospital is 100% operational
	Life safety	\$ 1,512,000				2 years repair w/ 5% capacity loss
	Collapse prevention	\$ 67,500,000				4 years of reconstruction
	Collapse	\$ 67,500,000				4 years of reconstruction
HVAC equipment	<b>Damage state</b>	<b>Repair/replacement cost per HVAC</b>			<b>Consequences per HVAC</b>	
	No	\$ 0			No capacity losses	
	Moderate	\$ 90,000			50% beds lost for 2 days	
	Extensive	\$ 500,000			50% beds lost for 20 days	
Piping	<b>Damage state</b>	<b>Repair/replacement cost per wall</b>			<b>Consequences per wall</b>	
	No	\$ 0			No capacity losses	
	Minor	\$ 230			Beds unavailable for 1 day	
	Moderate	\$ 460			Beds unavailable for 2 days	
	Extensive	\$ 690			Beds unavailable for 3 days	
	Complete failure	\$ 920			Beds unavailable for 3 days	
Partition wall	<b>Damage state</b>	<b>Repair/replacement cost per floor</b>				<b>Consequences per floor</b>
		<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	
	Slight	\$1,100	\$1,690	\$1,690	\$900	No capacity losses
	Moderate	\$1,720	\$4,380	\$4,380	\$2,290	10% beds lost for 7 days
Extensive	\$1,860	\$4,950	\$4,950	\$2,290	25% beds lost for 30 days	

### System Resilience and the RDAT

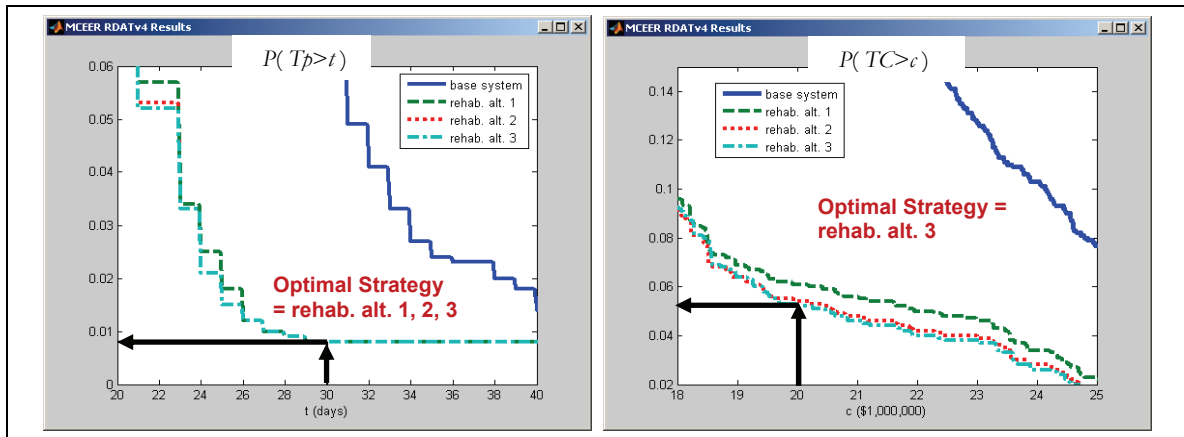
Rehabilitation decision analysis toolbox (RDAT) is a MATLAB based program for calculating the seismic resilience of structural/nonstructural systems in a health care facility. Using the RDAT it is possible to (i) compare the effectiveness of different rehabilitation alternatives for structural and nonstructural systems using the estimates of life cycle losses, and (ii) develop rational rehabilitation alternatives for increasing the seismic resilience of these systems. RDAT version 1 is limited to linear single degree of freedom structural/nonstructural systems and is available on the MCEER Users Networks at [http://civil.eng.buffalo.edu/users\\_ntwk/index.htm](http://civil.eng.buffalo.edu/users_ntwk/index.htm). RDAT version 2 extends to linear multi degree of freedom systems and is presented in detail in Kafali and Grigoriu (2005b). The final version of the RDAT with an application to the MCEER West Coast Demonstration hospital will be made available to the MCEER Users Networks by Fall 2007.

Figure 3 shows the histograms of the (a) total time  $T_p$  the system operates below 90% capacity in 50 years, and (b) total cost  $TC$  in 50 years, for the base system and the three rehabilitation alternatives, calculated by Monte Carlo simulation using 1000 samples.



**Figure 3. Histograms of  $T_p$  and  $TC$ .**

Figure 4 shows  $P(T_p > t)$  and  $P(TC > c)$ . A possible measure for comparing the effectiveness of different rehabilitation alternatives can be the probability that the total time the system operates below 90% capacity exceeds a level  $t_{cr}$  (or similarly, the probability that the total cost exceeds a level  $c_{cr}$ ). Accordingly, the optimal solution is the one with the lowest  $P(T_p > t_{cr})$  (or  $P(TC > c_{cr})$ ) and depends on the selected value of  $t_{cr}$  (or  $c_{cr}$ ). For example, Figure 4 shows that the optimal solutions are rehab. alt. 1, 2 and 3 for  $t_{cr} = 30$  days (or rehabilitation alternative 3 for  $c_{cr} = \$20,000,000$ ).



**Figure 4. Optimal rehabilitation strategy.**

### Concluding Remarks

A method was developed to identify an optimal retrofitting technique for structural/nonstructural systems. The method (i) considers a realistic seismic hazard model rather than using the maximum credible earthquake, (ii) 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 (iii) is designed for individual facilities rather than a large population of them. The method is based on

Monte Carlo simulation, probabilistic seismic hazard, fragility surfaces and capacity/cost analyses and is applied to the MCEER West Coast Demonstration Hospital.

## Acknowledgements

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