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# Seismic Resilience of a Regional System of Hospitals

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## Summary

*The concepts of seismic resilience and its quantitative evaluation are presented. The evaluation is based on non-dimensional analytical functions related to loss variation within a specified "recovery period", recovery function and fragility functions. The path to recovery usually depends on available resources and may take different shapes which can be estimated by proper recovery functions. Loss functions include both direct and indirect losses that are uncertain in themselves due to the uncertain nature of earthquake and structural behavior as well as due to uncertain description of functional limit states. Therefore, losses are functions of fragility of systems' components that are determined and combined together through use of multidimensional performance limit thresholds. The formulated framework is applied and exemplified for a complex system of six hospitals located in Memphis Tennessee, considering direct and indirect losses in its physical system and in the population served by the system. The example presented shows that for high system functionality values $Q(t)$, the marginal recovery cost doubles the cost associated to lower functionality values.*

## Introduction

MCEER performance assessment methodology (Resilience) is primarily developed to improve decision making procedures with regards to seismic performance of facilities and systems in general. In MCEER terminology, Seismic Resilience is a decision variable ($DV$) and a quantifiable measure of seismic performance that describes the recovery from a given loss required to maintain the function of the system with minimal disruption. Seismic resilience framework can compare losses and different pre and post event measures in order to verify if strategies and actions can reduce or eliminate disruptions in presence of seismic events. In previous studies, Bruneau et al., (2003) defined a fundamental framework for evaluating community resilience without any actual quantification and implementation. They offered a very broad definition of resilience to cover all actions that reduces losses from hazard, including mitigation and more rapid recovery. Chang et al., (2004) proposed a series of quantitative measures of resilience and applied them to a case study of an actual community, the seismic mitigation of the Memphis water system. Researchers at MCEER have developed a framework equation on the basis of concept of conditional probability and total probability theorem that attempts to provide a quantitative definition of resilience (Cimellaro et al., 2006b). In this paper the formulated framework is applied and exemplified for a complex system of six hospitals located in Memphis, Tennessee.

## Analytical formulation

In order to obtain a realistic quantification of the uncertainties of Resilience, various sources of uncertainties are incorporated in the framework equation. They are related to losses, function of recovery and time of recovery and combined in a unique quantity called "Resilience". In this framework the following uncertainties are considered and modelled as random variables: (a) uncertainties of the ground motion; (b) uncertainties of the structural response; (c) uncertainties of the limit states; (d) uncertainties in the estimation of the losses; (e) uncertainties in the estimation of the time of Recovery (Tre) and (f) uncertainties in the function of recovery. All these information are summarized in Equation (1) and visualized in Figure 1:

$$\overline{\mathrm{R}}=\frac{1}{\mathrm{N_I}}\sum_{I=1}^{N_I}\left\{\frac{1}{\mathrm{N_E}}\sum_{E=1}^{N_E}\frac{1}{\mathrm{T_{RE}}}\int_{t_{0E}}^{t_{0E}+T_{RE}}\left\{1\text{-}\mathrm{L}\left(\mathrm{I},\mathrm{T_{RE}}\right)\left[H\left(\mathrm{t}\text{-}\mathrm{t_{0E}}\right)-H\left(\mathrm{t}\text{-}\left(\mathrm{t_{0E}}+T_{RE}\right)\right)\right]\alpha_{\mathrm{R}}f_{\mathrm{Rec}}\left(t,t_{0E},T_{RE}\right)\right\}dt\;p_E\left(0,T_{LC}\right)\right\}P\left(I\right) \qquad (1)$$

where $N_E$ is the number extreme events expected during the lifespan (or control period) $T_{LC}$ of the system, $N_I$ is the number of different extreme events intensities expected during the lifespan (or control period) $T_{LC}$ of the system; $T_{RE}$ is the recovery time from event $E$; $t_{0E}$ is the time of occurrence of event $E$; $L(I,T_{RE})$ is the normalized loss function; $f_{REC}\ (t,\ t_{0E},\ T_{RE})$ is the recovery function; $P(I)$ is the Probability that an event with intensity $I$ happens in a given time interval $T_{LC}$; $p_E(0,T_{LC})$ is the probability that an event happens $E$ times in a given time interval $T_{LC}$; $\alpha_{\mathrm{R}}$ is a recovery factor and $H(t_0)$ is the Heaviside step function. In equation (1) there are the loss function $L(I,T_{RE})$, the recovery function $f_{REC}\ (t,t_{0E},T_{RE})$ and the fragility function that does not appear explicitly, but it is included in the loss function that will be defined in the following section.

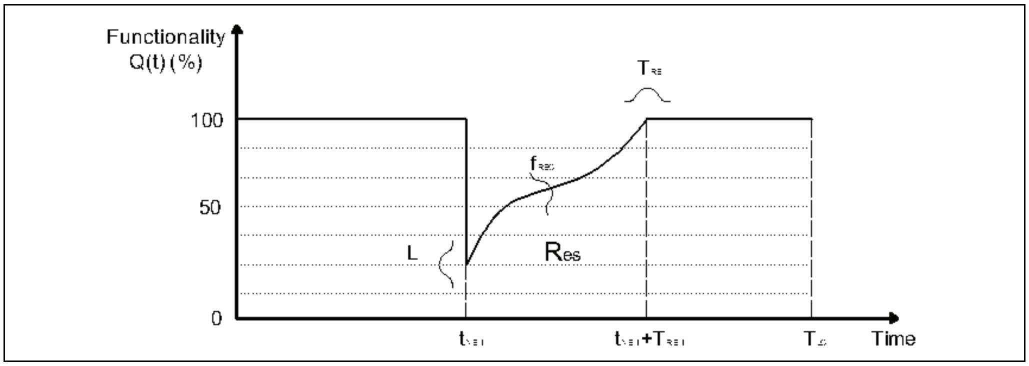


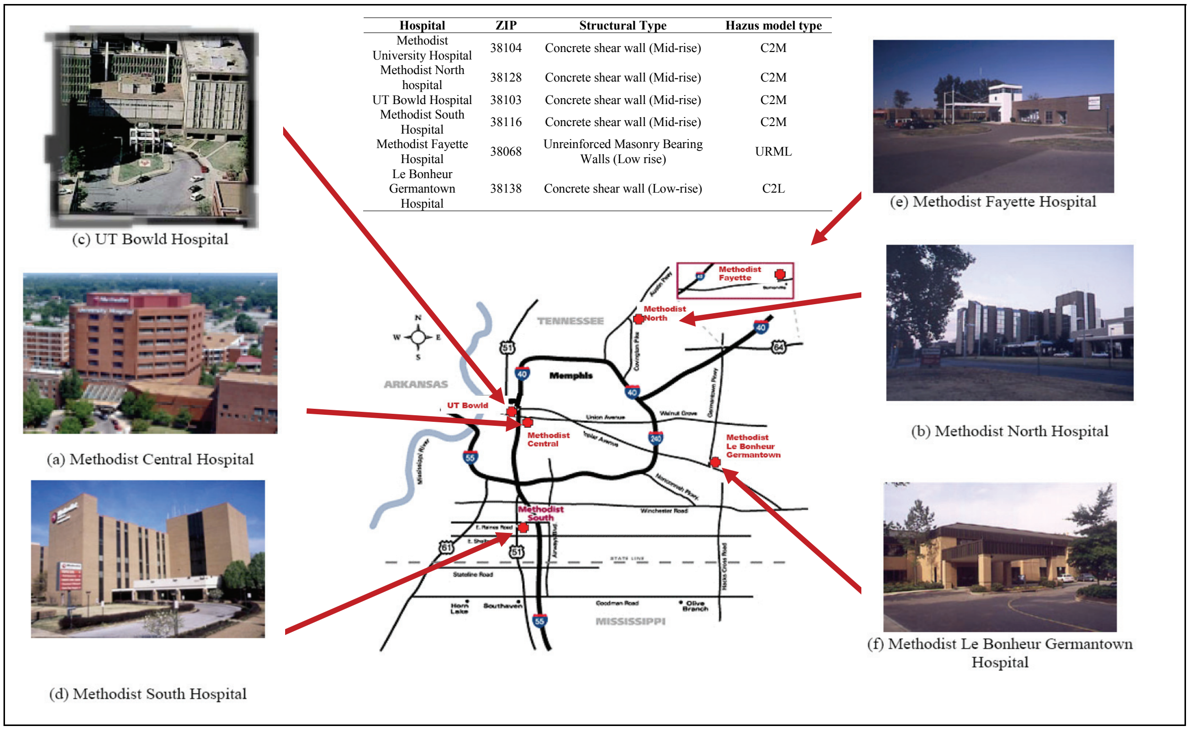
**Figure 1. Resilience**

## Case study: complex of six hospitals located in Memphis

To illustrate the proposed framework equation a complex of six hospitals located in Memphis, Tennessee has been used (Figure 2). It consists of a regional loss estimation study aimed at the estimation of economic losses of several buildings within a geographical region like a city. Figure 2 shows the locations (by Zip code) that are used to define the seismic Hazard (U.S.G.S. 2002) and the structural type of the hospitals that are used to define the structural vulnerability (HAZUS 2005). Four seismic rehabilitation alternative schemes are considered for each structural type: 1) *no action*; 2) *rehabilitation to life safety level*; 3) *rehabilitation to immediate occupancy level*; 4) *construction of a new building.* These rehabilitation levels are, as defined in FEMA 276 (1999), the target performance levels for rehabilitation against an earthquake. The initial rehabilitation costs for the options considered here are obtained from FEMA 227 (1992) and FEMA 156 (1995), which provide typical costs for rehabilitation of existing structures taking into account many factors, such as building type, earthquake hazard level, desired performance level, occupancy or usage type.

Fragility curves for each rehabilitation alternative (as defined in FEMA 276) are obtained directly correlating to the HAZUS code levels. Therefore, the HAZUS code levels are assigned to the rehabilitation levels mentioned above with reasonable assumptions (e.g. it is assumed that the “No Action” option, corresponds to the low code level). Fragility curves are developed for structural damage and nonstructural damage of drift sensitive and accelerations sensitive components using the HAZUS approach. Then fragility curves are combined together using the multidimensional fragility approach (Cimellaro et al. 2006a). Figure 3 shows fragility curves of structural damage for concrete shear walls mid rise building type (C2M). They are plotted for different damage states and are function of earthquake intensity measures that in this case is considered in term of return period.

The time control period $T_{LC}$ for a decision analysis is based on the decision maker’s interest in evaluating the alternatives. Generally, building system rehabilitation is better justified with longer time period, because the expected seismic losses associated with seismically vulnerable structure increases with longer time period. On the other hand a decision maker would feel more favorable to rehabilitation of structures when the rehabilitation is justified with shorter time period. Therefore, the time control period of the system $T_{LC}$ is assumed to be 30 years and a discount annual rate r of 6% is assumed. Figure 4 shows a comparison of structural damage distributions for two time control periods $T_{LC}$=30 yrs and $T_{LC}$=50 yrs for C2M type structures. As expected the probability of having no damage increases with shorter time periods.



| Hospital | ZIP | Structural Type | Hazus model type |
|---|---|---|---|
| Methodist University Hospital | 38104 | Concrete shear wall (Mid-rise) | C2M |
| Methodist North hospital | 38128 | Concrete shear wall (Mid-rise) | C2M |
| UT Bowld Hospital | 38103 | Concrete shear wall (Mid-rise) | C2M |
| Methodist South Hospital | 38116 | Concrete shear wall (Mid-rise) | C2M |
| Methodist Fayette Hospital | 38068 | Unreinforced Masonry Bearing Walls (Low rise) | URML |
| Le Bonheur Germantown Hospital | 38138 | Concrete shear wall (Low-rise) | C2L |

(c) UT Bowld Hospital

(e) Methodist Fayette Hospital

(a) Methodist Central Hospital

(b) Methodist North Hospital

(d) Methodist South Hospital

(f) Methodist Le Bonheur Germantown Hospital

Figure 2. System definition (Park, 2004)

Using the damage probability distributions (Figure 4), various seismic losses associated with the system are estimated using HAZUS approach (Table 1). It is assumed that losses of different hospitals units are independent, so the total loss of the system can be obtained by simply adding different losses. Then, losses ($L$) are combined using the approach described in Cimellaro et al., (2006b) and recovery time ($T_{RE}$) are estimated for the four earthquake levels and loss hazard curves are generated to calculate the overall expected loss. The values of seismic resilience are calculated according to Equation (1) for different damage states that are function of the seismic input.

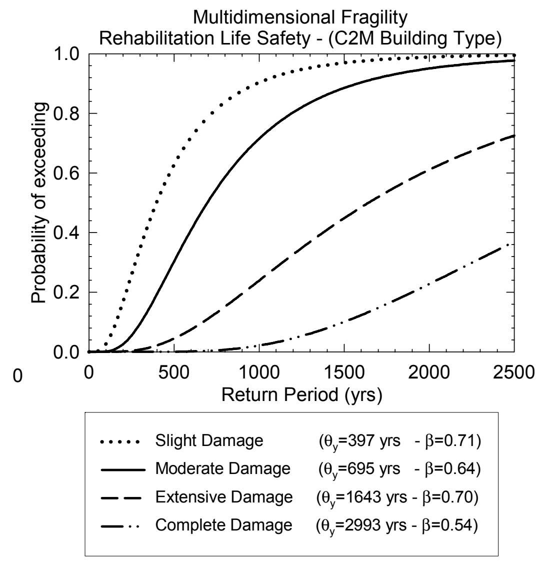


**Figure 3. Multidimensional fragility curves for C2M type structure -Rehabilitation to Life Safety**

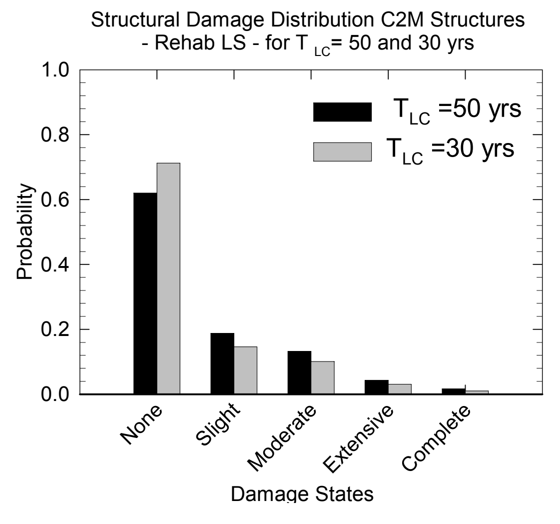


**Figure 4. Structural damage distribution for different rehabilitation strategies ($T_{LC}$=30 yrs) for C2M type structure - Rehabilitation to Life Safety**

**Table 1. Normalized losses for different Damage States of C2M buildings (HAZUS, 2005)**

| | | Slight | Moderate | Extensive | Complete | Complete [$/ft$^2$] |
|---|---|---|---|---|---|---|
| **LS** | **Structural Repair Cost** | 0.0176 | 0.1 | 0.5 | 1 | 17 |
| **LNS,DE** | **Drift Sensitive nonstructural Cost** | 0.0190 | 0.1 | 0.5 | 1 | 42 |
| | **Acceleration Sensitive nonstructural Cost** | 0.0194 | 0.1 | 0.3 | 1 | 62 |
| | **Contents Loss** | 0.020 | 0.1 | 0.5 | 1 | 60.5 |
| **LNS,DC** | **Death** | 0 | 0 | 0.000015 | 0.125 | |
| | **Injury** | 0 | 0.0003 | 0.001005 | 0.225 | |
| | **Recovery Time (days)** | 2 | 67.5 | 270 | 360 | |

In order to get rid of the seismic input its value is normalized using the four different hazard levels considered in this case. After normalization the values can be evaluated for different rehabilitation strategies (Figure 5).

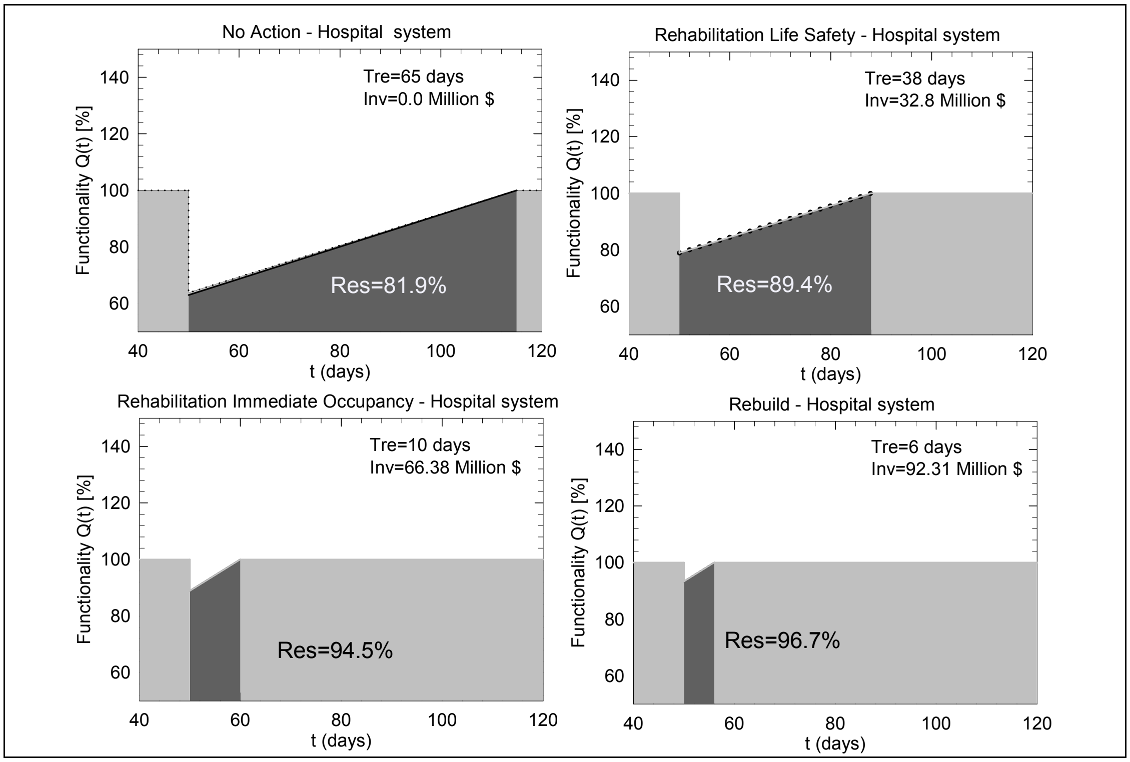


**Figure 5. Resilience for different rehabilitation strategies**

**Table 1. Rehabilitation costs, Recovery time and Seismic Resilience for different rehabilitation strategies.**

| Rehabilitation Alternatives | Rehabilitation Costs [$ Million] | Expected earthquake Loss [$ Million] | Total Costs[*] [$ Million] | Recovery Time $T_{RE}$ [days] | Resilience Res [%] |
|---|---|---|---|---|---|
| No Action | 0 | 32.34 | 119.64 | 65 | 81.9 |
| Life Safety (LS) | 32.8 | 18.86 | 138.96 | 38 | 89.4 |
| Immediate Occupancy (IO) | 66.38 | 9.54 | 163.22 | 10 | 94.5 |
| Rebuild | 92.31 | 5.82 | 185.43 | 6 | 96.7 |

The initial costs of rehabilitation for different rehabilitation strategies, the average recovery time and resilience values are summarized in Table 1. For this case study it is shown that the *Rebuild Option* is able to obtain the biggest value of seismic Resilience (96.7%) if compared with the other three

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[*] It includes cost of the entire system (87.3 Million $) + cost of rehabilitation + cost of loss recovery

rehabilitation strategies (Table 1), but it is also the most expensive solution (92.31 millions $). However, if No Action is taken the value of seismic resilience is still reasonable high (81.9%). As shown in this case study initial investments and resilience are not linearly related. When the functionality Q(t) is very high in order to improve it of small percentage is necessary to invest a huge amount of money respect to the case when the functionality of the system is low.

## Concluding Remarks

The definition of seismic resilience combines information from technical and organizational fields, from seismology and earthquake engineering to social science and economics. So it is clear that many assumptions and interpretations are found to be made in the study of seismic resilience, but the final goal is to integrate the information from these different fields into a unique function leading to results that are unbiased by uninformed intuitions or preconceived notions of risk. The goal of this paper is to provide a quantitative definition of resilience in a rational way through the use of an analytical function that may fit both technical and organizational issues. A regional complex of six hospitals has been used to illustrate the applicability of the framework. The example shows that double the amount of money to improve resilience of 5.1% from 89.4% to 94.5% should be invested to improve resilience of 1.2% from 94.5 to 96.7%. However, it is important to note that the assumptions made herein are only representative for the case presented. For other problems users calculating resilience are advised to focus on the assumptions that mostly affects the problem at hand.

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