

MCEER's vision on the seismic resilience of health care facilities

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ABSTRACT:

The concept of seismic resilience needs a quantitative evaluation. The evaluation suggested in this paper is based on nondimensional analytical functions related to variations of losses within a specified “recovery period”. The resilience refers to both direct and indirect losses. The path to recovery usually depends on available resources and may take different shapes, which can be estimated by proper recovery functions. The loss functions have major uncertainties due to the uncertain nature of the earthquake and structural behavior as well as due to uncertain description of functionality limits. Therefore, losses can be described as functions of fragility of systems' components. Fragility curves can be determined using multidimensional performance limit thresholds, which allow considering simultaneously different mechanical-physical variables such as forces, velocities, displacements and accelerations along with other functional limits. A procedure, which defines resilience as function of losses and loss recovery based on multidimensional system fragility, is formulated and an example is presented for a typical California hospital.

1 INTRODUCTION

Recent events have shown how habitat systems (structures, communities, regions, etc.) are vulnerable to natural disasters of various kinds such as human errors, systems failures, pandemic diseases and malevolent acts, including those involving cyber systems and weapon of mass destruction (chemical, biological, radiological). Hurricane Katrina clearly demonstrated the need for improving the local disaster management plans of different federal, state and private institutions. In order to reduce the losses in these systems the emphasis may have to shift to mitigation and preventive actions to be taken before the extreme event happens. Mitigation actions can reduce the vulnerability of a system; however, if mitigation is insufficient, or the event exceeds expectations, community should be prepared to recover rapidly, showing a resilient behavior. Therefore, there is a need for cost-effective mitigation of potential and actual damage that may result in disruptions, particularly those causing cascading effects capable of incapacitating a system, or an entire region, and those impeding response and recovery.

Seismic resilience as defined in this paper is the

capability to recover from an undesirable loss in order to maintain the function of the system with minimal disruption. Therefore, while mitigation may emphasize use of technologies and implementation of policies to reduce losses, the resilience function considers also the recovery process, including behavior of individuals and organizations in face of disasters. A wealth of information is available on specific actions, policies or scenarios that can be adopted to reduce the direct and indirect immediate economic losses resulting from earthquakes, but there is little information on procedures on how to quantify these actions and policies as function of time. Seismic resilience functions can compare losses and different pre- and post-event measures in order to verify whether these strategies and actions can reduce, or eliminate, disruptions in presence of seismic events.

Bruneau *et al.* (2003) offered a very broad definition of resilience to cover all actions that reduce losses from hazard, including effects of mitigation and rapid recovery. The above paper defined the earthquake resilience of the community as “the ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in

ways to minimize social disruption and mitigate the effectors of future earthquakes”. These authors suggested that resilience can be conceptualized along four dimensions: technical, organizational, social and economic (TOSE). The two components technical and economic are more related to the resilience of critical physical systems, such as lifeline systems and essential facilities. The other two components organizational and social are more related to the community affected by the physical systems. The above paper defined a fundamental framework for evaluating community resilience without detailed quantification and implementation. Chang *et al.* (2004) proposed a series of quantitative measures of resilience and demonstrated them in a case study of an actual community, the seismic mitigation of Memphis water system. The present paper attempts to provide a quantitative definition of resilience using analytical function which allowing identification of quantitative measures of resilience.

2 DEFINITIONS AND FORMULATIONS

To establish a common frame of reference a unified terminology is proposed, the fundamental concepts of resilience are analyzed, and an applications to a health care facilities is presented:

Resilience is defined as a function indicating the capability to sustain a level of functionality or performance for a given building, bridge, lifeline, networks or community over a period of time T_{LC} (life cycle, life span etc.) In particular, the system is affected by sudden losses of functionality followed by a recovery within a period, T_{RE} .

The control time T_{LC} for which the resilience is evaluated is usually decided by ownership, or society (usually life cycle, life span etc.).

The recovery time T_{RE} is the time necessary to restore the functionality of an infrastructure system to a desired level that can operate or function the same, close to, or better than the original one.

The recovery time T_{RE} is a random variable with high uncertainties that includes the construction recovery time and the business interruption time and it is usually smaller than T_{LC} . It typically depends on the earthquake intensities and the location of the extreme event that may happen in a system with given resources such as capital, materials and labor following a major seismic event. For these reasons, this is the most difficult quantity to predict in the resilience function. Porter *et al.* (2001) attempted to make distinction between downtime and repair time, and tried to quantify the latter. In that work, damage states were combined with repair duration, and with prob-

ability distributions to estimate assembly repair durations. Others researchers calculate the recovery period in various ways as indicated further in this paper. While the previous definitions apply to structures, infrastructure or societal organizations, a more general application of such definitions is “a disaster resilient community”.

Disaster resilient community is a community that can withstand an extreme event, natural or man made, with a tolerable level of losses, and is able to take mitigation actions consistent with achieving that level of protection. (Mileti 1999)

The seismic performance of the system is measured through a unique decision variable (DV) defined as “Resilience” that combines other decision variables (economic losses, casualties, recovery time etc.) which are usually employed to judge seismic performance. This Resilience is defined graphically as the normalized shaded area underneath the functionality of a system, defined as $Q(t)$. $Q(t)$ is a non stationary stochastic process and each ensemble is a piecewise continuous function as the one shown in Figure 1, where the functionality $Q(t)$ is measured as a nondimensional (percentage) function of time. For a single event, the resilience is given by the following equation (Bruneau *et al.* 2005):

$$r_i = \int_{t_{0E}}^{t_{0E} + T_{RE}} Q(t) dt; \quad (1)$$

where:

$$Q(t) = 1 - L(I, T_{RE}) \cdot \left[H(t - t_{0E}) - H(t - (t_{0E} + T_{RE})) \right] \cdot \alpha_R \cdot f_{Rec}(t, t_{0E}, T_{RE}) \quad (2)$$

where $L(I, T_{RE})$ is the loss function; $f_{REC}(t, t_{0E}, T_{RE})$ is the recovery function; α_R is a recovery factor and $H(t_0)$ is the Heaviside step function, T_{LC} is the control time of the system, T_{RE} is the recovery time from event E and; t_{0E} is the time of occurrence of event E . When including all uncertainties in the problem, the expression of resilience becomes:

$$\bar{R} = \sum_{T_{RE}}^{N_{TRE}} \sum_L^{N_L} \sum_{DM}^{N_{DM}} \sum_R^{N_R} \sum_i^{N_i^*} r_i \cdot P(T_{RE}/L) P(L/DM) P(DM/R) \cdot P(R/I) P(I_{T_{LC}} > i^*) \Delta I \cdot \Delta R \cdot \Delta DM \cdot \Delta L \cdot \Delta T_{RE}; \quad (3)$$

In details, six sources of uncertainties are considered in this framework: i) intensity measures I ; ii) Response parameters \mathbf{R} ; iii) performance threshold \mathbf{r}_{lim} ; iv) damage measures, DM ; v) losses L ; vi) recovery time T_{RE} . The methodology that is summa-

rized in Equation(3) is more general than that proposed by Cimellaro *et al.* (2005), because in that framework only the uncertainties of the intensity measure I were taken into account, whereas in this framework all uncertainties involved are considered.

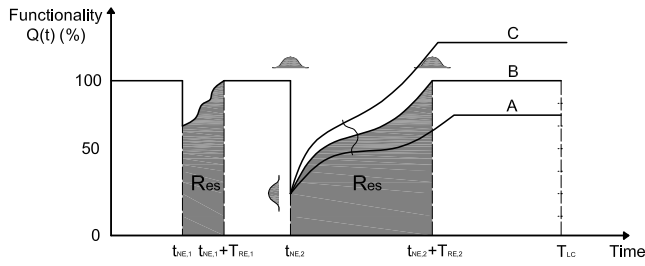


Figure 1 Uncoupled Resilience

The conditional probabilities in Equation (3) related to the various uncertainties considered are: $P(I_{T_{LC}} > i^*)$, the probability of exceeding a given ground motion parameter i^* in a time period T_{LC} ; $P(R/I)$ reflecting the uncertainties in the structural analysis parameters (uncertainties of the structural parameters and uncertainties of the model itself); $P(DM/R)$ describes the uncertainties in the damage estimation; $P(L/DM)$ describes the uncertainties in the loss estimation, while $P(T_{RE}/L)$ describes the uncertainties in the time of recovery.

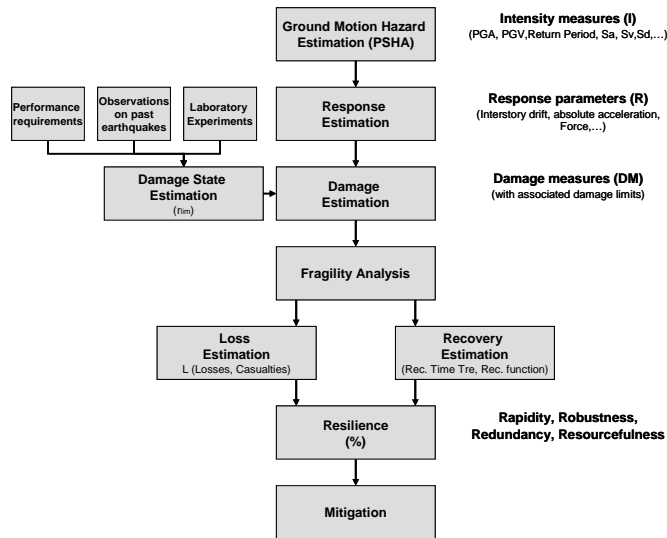


Figure 2 MCEER performance assessment methodology

$P(I_{T_{LC}} > i^*)$ in Equation(3) can be obtained from probabilistic seismic hazard analysis (PSHA). A common approach involves the development of *seismic hazard curves*, which indicate the average annual rate of exceedance λ_{i^*} of different values of the selected ground motion parameter i^* . When combined with the Poisson model, the probability $P(I_{T_{LC}} > i^*)$ of exceeding the selected ground motion parameter i^* in a specified period of time T_{LC} , takes the form:

$$P(I_{T_{LC}} > i^*) = 1 - e^{-\lambda_{i^*} T_{LC}} \quad (4)$$

The control time T_{LC} for a decision analysis is based on the decision maker's interest in evaluating the alternatives, as it will be discussed subsequently in the case study, herein.

The system diagram in Figure 2 identifies the key steps of the framework to quantify resilience.

3 DIMENSIONS OF RESILIENCE

Researchers at the Multidisciplinary Center for Earthquake Engineering Research (MCEER, Bruneau, *et al.* 2003) have identified 4 dimensions along which resilience can be improved. These are *robustness, resourcefulness, redundancy, and rapidity*. These dimensions can better be understood by looking at the functionality curve shown in Figure 3 and Figure 4.

Rapidity is the “*capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption*” (Bruneau *et al.* 2003)

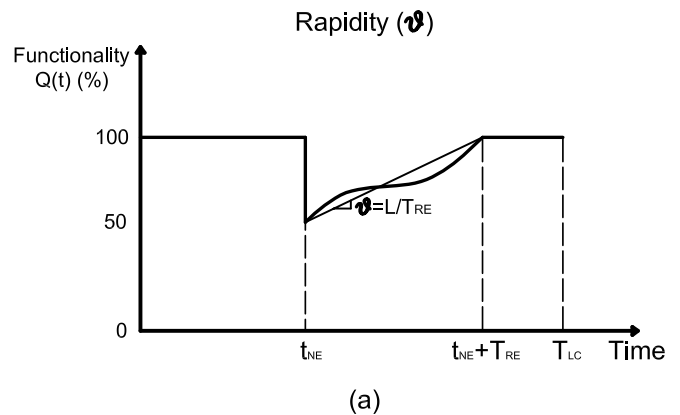


Figure 3 Dimensions of resilience: Rapidity

Mathematically it represents the slope of the functionality curve (Figure 3) during the recovery time:

Robustness referring to engineering systems is, “*the ability of elements, systems or other units of analysis to withstand a given level of stress, or demand without suffering degradation or loss of function*” (Bruneau *et al.* 2003).

In other words, it is the residual functionality right after the extreme event (Figure 4). During an earthquake, losses always occur, so mean losses are there, however one way to increase robustness in the system is to reduce the dispersion in the loss estimation represented by σ_L . In this definition robustness is the capacity to predict the functionality of the system after the extreme event, keeping variability

within a narrow band, independently of the event itself.

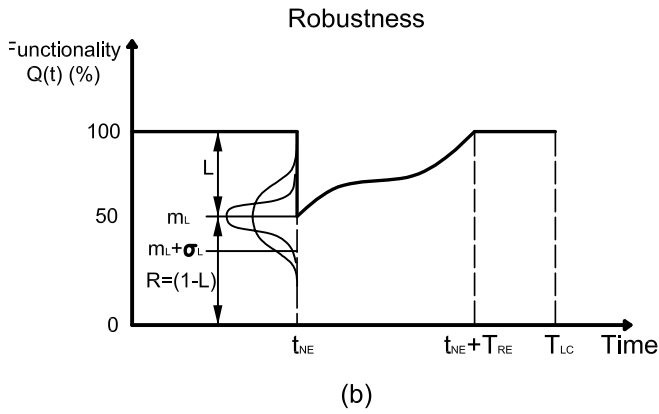


Figure 4 Dimensions of resilience: Robustness

Redundancy is “the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e. capable [of] satisfying functional requirements in the event of disruption, degradation, or loss of functionality” (Bruneau et al. 2003).

Simply, it describes the availability of different resources in the loss or recovery process. Redundancy is a very important attribute of resilience, since it represents the capability to use alternative resources, when the principal ones are either insufficient or missing.

Redundancy should be developed in the system in advance and it should exist in a latent form as a set of possibilities to be enacted through the creative efforts of responders (Resourcefulness).

Resourcefulness is “the capacity to identify problems, establish priorities, and mobilize resources when condition exist that threaten to disrupt some element, system, or other unit of analysis” (Bruneau et al., 2003).

This is a property difficult to quantify since it mainly depends on human skills and improvisation during the extreme event. Resourcefulness and Redundancy are strongly interrelated. For example, resources, and resourcefulness, can create redundancies that did not exist previously. In fact, one of the major concerns with the increasingly intensive use of technology in emergency management is the tendency to over-rely on these tools, so that if technology fails, or it is destroyed, the response falters. To forestall this possibility, many planners advocate **Redundancy**.

4 LOSS FUNCTION

Loss estimation and in particular the losses associated with extreme events, require first of all some damage descriptors that can be translated into

monetary terms and other units that can be measured, or counted, e.g. the number of people requiring hospitalization. The loss estimation procedure is by itself a source of uncertainty and this has been taken into account in Equation (3). Loss estimation procedure is described in this section as an example, however users can adopt their preferred methodology to estimate the losses L and use them in Equation(1) and (2) for evaluating the resilience of systems.

Earthquake losses are by their very nature highly uncertain, and are different for every specific scenario considered. However, some common parameters affecting loss can be identified. In fact the loss function $L(I, T_{RE})$ is expressed as a function of earthquake intensity I and recovery time T_{RE} . Losses can be divided into two groups based on engineering considerations: **Structural losses** (L_S) and **Non Structural losses** (L_{NS}) that are added together.

For simplicity L_S and L_{NS} are described with reference to a particular essential facility as a hospital, so that the physical structural losses can be expressed as ratios of building repair and replacement costs as follows:

$$L_S(I) = \sum_{j=1}^5 \left[\frac{C_{S,j}}{I_S} \cdot \prod_{i=1}^{T_i} \frac{(1 + \delta_i)}{(1 + r_i)} \right] \cdot P_j \left\{ \bigcup_{i=1}^n (R_i \geq r_{limi}) / I \right\} \quad (5)$$

where P_j is the probability of exceeding a performance limit state j conditional an extreme event of intensity I occurs also known as the fragility function. $C_{S,j}$ are the building repair costs associate with a j damage state; I_S are the replacement building costs; r is the annual discount rate; t_i is the time range in years between the initial investments and the occurrence time of the extreme event; δ_i is the annual depreciation rate. The nonstructural losses L_{NS} consist of four contributions: (i) Direct economic losses $L_{NS,DE}$ (or Contents losses); (ii) Direct Causalities losses $L_{NS,DC}$; (iii) Indirect economic losses $L_{NS,IE}$ (or Business interruption losses); (iv) Indirect Causalities losses $L_{NS,IC}$.

An important key factor in loss estimation is the determination of conversion factors for non-monetary values, like the value of human life, that are used in equivalent cost analysis. In order to avoid this problem direct causalities losses $L_{NS,DC}$ are expressed as a ratio of the number of injured or dead N_{in} (the two groups can be considered separately, but in this formulation are grouped for simplicity) and the total number of occupants N_{tot} :

$$L_{NS,DC}(I) = \frac{N_{in}}{N_{tot}} \quad (6)$$

The number of injured people N_{in} in fatal and nonfatal manner depends on multiple factors such as, the *time of day of earthquake occurrence, the age*

of the population and the number and proximity of available health care facilities.

The number and proximity of available hospitals determine the proportion of fatalities among the seriously injured. In order to estimate risk by mean of resilience function it is necessary to make empirical predictions of casualties based on structural damage or ground motion intensity. HAZUS (FEMA 2005) reports casualty severity levels as function of ground motion intensity. Peek-Asa found that for the 1994 Northridge earthquake the ground motion levels as measured by MMI were better predictor of casualty rates than building damage because the number of people injured in locations where structural damage occurred was only a small fraction of the total number of injured. For example, minor injuries resulted from being struck by objects and from falling, and not by structural damage. MMI allows a rough estimate of casualty rates, based on the population that is subjected to various intensities levels. The **indirect economic losses** $L_{NS,IE}(I, T_{RE})$ are time dependent compared to all the previous losses considered. Among the post-earthquake losses these are the most difficult to quantify, because of the different forms they can take. They mainly consist of *business interruptions, relocation expenses, rental income losses, etc.* Losses of revenue, either permanent or temporary, can be caused by damage to structures and contents, and this is most important for manufacturing and retail facilities, and to lifelines, because damage to the former can mean less ability to deliver resources and services, like electricity, water, natural gas, or transportations. Losses due to business interruption should be modeled considering both the structural losses L_S , and the time necessary to repair the structure T_{RE} . These two quantities are not independent, but are related because the recovery time T_{RE} increases with the extent of structural damage $L_S(I)$. In addition, indirect casualties losses (L_{IC}) belong to this group. They describe the number of people that are injured or that die because of hospital dysfunction. For a hospital, L_{IC} can also be expressed in the form of Equation(6). The total non-structural losses L_{NS} can be expressed as a combination of the total direct losses $L_{NS,D}$ and the total indirect losses $L_{NS,I}$. Also direct $L_{NS,D}$ and indirect losses $L_{NS,I}$ are expressed as combination of economic ($L_{NS,IE}$, $L_{NS,DE}$) and casualties' losses ($L_{NS,IC}$, $L_{NS,DC}$). Further details can be found in Reinhorn *et al.* (2007).

5 RECOVERY FUNCTION

Most of the models available in literature, including the PEER equation framework (Cornell and Krawinkler, 2000), are loss estimation models that focus on initial losses caused by disaster, where losses are measured relative to pre-disaster condi-

tions. These totally ignore the temporal dimension of post-disaster loss recovery. As indicated in Figure 1 the *recovery time* T_{re} and the *recovery path* clearly make a great difference to evaluating resilience, so they should be estimated accurately. However, as shown in Figure 1 the system considered may not necessary return to the pre-disaster baseline performance. It may exceed the initial performance (Figure 1-curve C), when the recovery process ends, in particular when the system (e.g. community, essential facility, etc.) may use the opportunity to fix pre-existing problems inside the system itself. On the other hand, the system may suffer permanent losses and equilibrate below the baseline performance (Figure 1-curve A).

Not much literature is available about a comprehensive model that describes the recovery process. Miles and Chang (2006) set out the foundations for developing models of community recovery presenting a comprehensive conceptual model and discussing some issues related. Once these complex recovery models are available it is possible to describe relationship across different scales-socioeconomic agents, neighborhood and community, and to study the effects of different policies and management plans in an accurate way.

In this paper, the recovery process is oversimplified using recovery functions that can fit to the more accurate results obtained with the Miles and Chang (2006) model.

Different types of recovery functions can be selected depending on the system and society preparedness response. For example, three possible recovery functions are: (i) *linear*, (ii) *exponential* (Kafali and Grigoriu 2005) and (iii) *trigonometric* (Chang and Shinozuka 2004). The simplest form is a linear recovery function that is generally used when there is no information regarding the preparedness, resources available and societal response. The exponential recovery function is used where the societal response is driven by an initial inflow of resources, but then the rapidity of recovery decreases as the process nears its end. Trigonometric recovery function is used when the societal response and the recovery are driven by lack of organization and/or resources.

6 FRAGILITY FUNCTION

The calculation of seismic resilience through functionality losses (Equation(2)) makes use of fragility, or reliability of a given system. Fragility curves are functions that represents the probability that the response $\mathbf{R} = \{R_1, \dots, R_n\}$ of a specific structure (or family of structures) exceeds a given threshold $\mathbf{r}_{lim} = \{r_{lim1}, \dots, r_{limn}\}$. The threshold is associated with a given limit state, conditional on earthquake intensity parameter I like peak ground

acceleration (Pga), peak ground velocity (Pgv), return period (T_r), spectral acceleration (Sa), spectral displacements Sd, modified Mercalli Intensity MMI etc. The response \mathbf{R} and the limit states \mathbf{r}_{lim} are expression of the same variable such as deformation, drift, acceleration, stresses, strains, (mechanical characteristics) or other functionality variables.

Response \mathbf{R} and response threshold \mathbf{r}_{lim} are functions of the structural properties of the system \mathbf{x} , the ground motion intensity I and the time t . However, in this formulation it is assumed that the response threshold $\mathbf{r}_{lim}(\mathbf{x})$ does not depend on the ground motion history and so does not depend on time, while the demand $R_i(\mathbf{x}, I, t)$ of the generic i^{th} component is replaced by its maximum value over the duration of the response history $R_i(\mathbf{x}, I)$. In the following, the dependence of the response $\mathbf{R}(\mathbf{x}, I)$ on \mathbf{x} and I , and the dependence of the response threshold $\mathbf{r}_{lim}(\mathbf{x})$ on \mathbf{x} will be omitted for convenience.

With these assumptions, the general definition of fragility can be written in the following form when the number of parameters that are involved is n :

$$F = P \left\{ \bigcup_{i=1}^n (R_i \geq r_{limi}) \right\} = \sum_i P \left\{ \bigcup_{i=1}^n (R_i \geq r_{limi}) / I = i \right\} P(I = i) \quad (7)$$

where R_i is the response parameter related to a certain quantity (deformation, force, velocity, etc.); r_{limi} is the response threshold parameter correlated with the performance level. Fragility explicitly appears in the expression of the loss function (5) where normalized losses are multiplied by P_j , the probability of exceeding a given performance level j conditional on an event of intensity I . This value can be obtained by the fragility function when the intensity I of the event is known. The definition of fragility in Equation (7) requires implicitly the definition of the performance limit state thresholds \mathbf{r}_{lim} that are discussed in the following section.

7 MULTIDIMENSIONAL PERFORMANCE LIMIT STATE FUNCTION

The calculation of fragility has been performed using a generalized formula describing the multidimensional performance limit state threshold (MPLT), and it allows considering multiple limit states related to different quantities in the same formulation (Cimellaro *et al.* 2006a). The multidimensional performance limit state function $L(r_{lim1}, \dots, r_{limn})$ for the n -dimensional case, when n different types of limit states are considered simultaneously, can be given by:

$$L(\mathbf{r}_{lim}) = \sum_{i=1}^n \left(\frac{r_{i,lim}}{r_{i,lim,0}} \right)^{N_i} - 1 \quad (8)$$

where $r_{i,lim}$ is the dependent response threshold parameter (deformation, force, velocity, etc.), that is correlated with damage; $r_{i,lim,0}$ is the independent capacity threshold parameter and N_i are the interaction factors determining the shape of n -dimensional surface. This model can be used to determine the fragility curve of a single nonstructural component, or to obtain the overall fragility curve for the entire building including its nonstructural components. Such function allows including different mechanical response parameters (force, displacement, velocity, accelerations etc.) and combining them together in a unique fragility curve. Different limit states can be modeled as deterministic, or random variables and they can be considered either linear, nonlinear dependent or independent using the desired choice of the parameters appearing in Equation(8). For example in a 2D-dimensional space (Figure 5), the response of the system can be visualized in a space where on the x-axis can be the spectral displacements S_d , while on the y-axis can be the pseudo spectral accelerations PSA and values on z-axis show the probability (shown by contour lines). The shape of the response curve of the system in this space is similar to a "bell surface" (Bruneau *et al.* 2004) while the multidimensional performance threshold (MPLT) in this space is represented by a cylindrical nonlinear function that relates acceleration performance threshold A_{LS} to displacement performance threshold D_{LS} . The probability that the response \mathbf{R} exceeds a specific performance threshold \mathbf{r}_{lim} can directly be calculated from the volume under the surface distribution exceeding the specified limit represented in Figure 5 by a dotted line. More details are given elsewhere (Cimellaro *et al.*, 2006a).

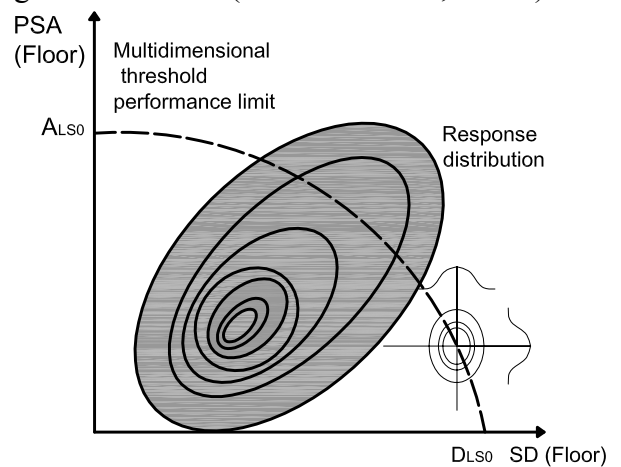


Figure 5 Multidimensional threshold limit state

8 CASE STUDY: DEMONSTRATION HOSPITAL

The methodology described above has been applied to a hospital, an essential facility in the San Fernando Valley in Southern California, chosen as a typical case study for MCEER thrust area 2. The hospital (W70) was constructed in the early 1970s to meet the seismic requirements of the 1970 Uniform Building Code (ICBO 1970, Yang *et al.* 2003). The lateral force resisting system consists of four moment-resisting frames in the north-south direction and two external moment-resisting frames in the east-west direction. Details about the description of the model can be found in Cimellaro *et al.* (2006a) and Viti *et al.* (2006). A computer program, IDARC2D (Reinhorn *et al.* 2004), has been used to perform the nonlinear time history analysis of the hospital using a two-dimensional inelastic MDOF model. A series of 100 synthetic near fault ground motions, described as the “MCEER series” (Wanitkorkul *et al.* 2005) corresponding to different return periods (250, 500, 1000 and 2500 years) has been used to determine the fragility curves of the building (Viti *et al.* 2006) using the procedure described by Cimellaro *et al.* (2006a). Losses have been determined according to HAZUS (FEMA 2005). The structural losses for this type of building have obtained as 0.2%, 1.4%, 7.0% 14.0% of the building replacement costs for the cases of slight, moderate, extensive and complete damage, respectively.

The nonstructural losses have been calculated as 1.8%, 8.6%, 32.8% 86% of the building replacement costs for the four damage states. The percentage of people injured for the different damage states is 0.05%, 0.23%, 1.1%, 6.02%, 75% (FEMA 2005) of the 400 people assumed inside the hospital and the 100 outside the hospital. Other losses such relocation costs, rental income losses and loss of income have also been considered using the procedure described in HAZUS for this type of building (COM6). The values of resilience functions for the four different hazard levels represented by probability of exceedance P in 50 years are reported in Table 1.

Table 1 Resilience and time of recovery vs. different hazard levels

Prob. of exceed. in 50 yrs (%)	Time of Recovery (days)	Resilience (%)
(1)	(2)	(3)
20	71	99.17
10	94	98.78
5	228	97.70
2	297	96.28

The resilience of the building is almost constant with the increase of earthquake intensity showing a good behavior of the building (Table 1). Comparing

the recovery curves $Q(t)$ it is noted, as expected, that there is a drop with increasing earthquake magnitude due to the increasing losses and consequentially on the effective recovery time (Figure 6). When combining resilience associated with different hazard levels, a final value of 98.7% is obtained.

Four different seismic retrofit schemes were considered for this case study to improve the seismic resilience of the hospital: a) Moment resisting frames (MRF); b) Unbonded or buckling restrained braces; c) Shear walls and d) Weakening and Damping (Viti *et al.* 2006). All retrofit strategies have been optimized with the procedure described in Viti *et al.* (2006) and Cimellaro *et al.* (2006c). Table 2 shows the values of resilience for the four different retrofit techniques and for different probability of exceedance. The resilience value shown in the last row of Table 2 considered the uncertainties of the ground motion parameters.

Table 2 Resilience vs. different hazard levels for different retrofit strategies

PE ₅₀ (%)	MRF	Resilience (%)			W+D
		UB	Shear Walls		
(1)	(2)	(3)	(4)	(5)	
20	98.6	99.0	98.6	99.5	
10	98.1	98.7	98.1	99.2	
5	97.4	97.9	97.4	98.2	
2	95.7	96.1	95.7	97.6	
avg	98.15	98.61	98.15	99.14	

The same values of Resilience (y-axis) as function of the annual probability of exceedance (x-axis) are shown in Figure 6. This shows that the best improvement in terms of resilience is obtained using a retrofit strategy based on weakening and damping. This retrofit technique produces both a reduction of displacements and of accelerations (Viti *et al.* 2006). The reduction of accelerations is important for hospitals, because many of building contents (nonstructural components) are acceleration sensitive.

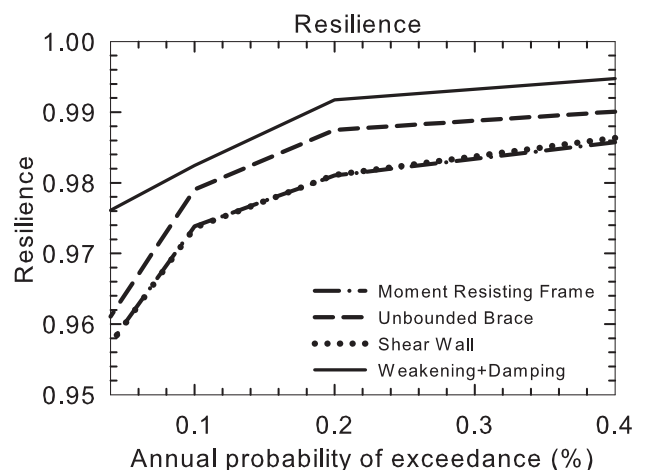


Figure 6 Comparison of different rehabilitation strategies in term of seismic resilience

9 CONCLUSIONS

The definition of seismic resilience combines information from technical and organizational fields, from seismology and earthquake engineering to social science and economics. The final goal is to integrate the information from these different fields into a unique function leading to results that are unbiased by uninformed intuition or preconceived notions of risk. The goal of this paper has been to provide a quantitative definition of resilience in a rational way using an analytical function that may fit both technical and organizational issues. An application of this methodology to health care facilities is presented in order to show the implementations issues.

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