Exploring the Concept of Seismic Resilience for Acute Care Facilities

Michel Bruneau,[a] M.EERI, **and Andrei Reinhorn,**[b] M.EERI

This paper explores the operational and physical resilience of acute care facilities, recognizing that the key dimension of acute care facilities is not a simple engineering unit. Quantification of resilience is first approached from the broader societal context, from which the engineering subproblem is formulated, recognizing that, to operate, hospitals depend intricately on the performance of their physical infrastructure (from the integrity of structural systems and nonstructural systems, lifelines, components, and equipment). Quantification relates the probability of exceeding floor accelerations and interstory drifts within a specified limit space, for the structural and nonstructural performance. Linear and nonlinear structural responses are considered, as well as the impact of retrofit or repair. Impact on time to recovery is considered in all cases. The proposed framework makes it possible to relate probability functions, fragilities, and resilience in a single integrated approach, and to further develop general tools to quantify resilience for sociopolitical-engineering decisions. [DOI: 10.1193/1.2431396]

INTRODUCTION

As part of the conceptualization of a framework to enhance the seismic resilience of communities (Bruneau et al. 2003), seismic resilience has been defined as the ability of a system to reduce the chances of a shock, to absorb such a shock if it occurs (abrupt reduction of performance), and to recover quickly after a shock (reestablish normal performance), as described in Bruneau et al. (2003). More specifically, a resilient system is one that shows the following:

- reduced failure probabilities,
- reduced consequences from failures, in terms of lives lost, damage, and negative economic and social consequences, and
- reduced time to recovery (restoration of a specific system or set of systems to their “normal” level of functional performance).

A broad measure of resilience that captures these key features can be expressed in general terms by the concepts illustrated in Figure 1, based on the notion that a measure, $Q(t)$, which varies with time, can be defined to represent the quality of the infrastructure of a community. Specifically, performance can range from 0% to 100%, where 100%

[a] Professor, Department of Civil, Structural, and Environmental Engineering, and Director, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, Buffalo, NY 14260
[b] Professor, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, Buffalo, NY 14260

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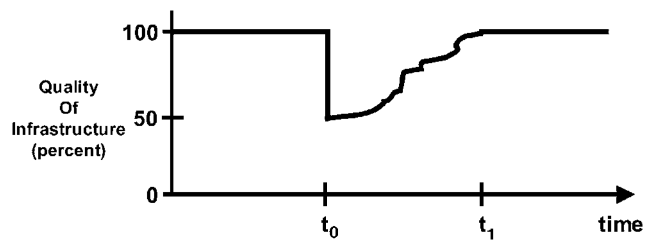

Figure 1. Schematic representation of seismic resilience concept (Bruneau et al. 2003).

means no degradation in quality and 0% means total loss. If an earthquake or other disaster occurs at time t_0, it could cause sufficient damage to the infrastructure such that the quality measure, $Q(t)$, is immediately reduced (from 100% to 50%, as for example in Figure 1). Restoration of the infrastructure is expected to occur over time, as indicated in that figure, until time t_1 when it is completely repaired and functional (indicated by a quality of 100%). Hence community earthquake loss of resilience, R, with respect to that specific earthquake, can be measured by the size of the expected degradation in quality (probability of failure), over time (that is, time to recovery). Mathematically, it is defined by

$$R = \int_{t_0}^{t_1} [100 - Q(t)]dt \tag{1}$$

Much research is needed to quantify resilience, particularly for certain types of critical facilities. For a geographically distributed system designed to provide a standardized service, such as a power grid or a water distribution network, the problem is simpler, as the vertical axis in Figure 1 could be a quantifiable value, such as kilowatts, gallons, or households provided with service. However, for critical systems for which the deliverable is not a simple engineering unit, such as for the case of acute care facilities, the vertical axis is harder to define, not to mention quantify.

This paper presents concepts developed in attempts to quantify the seismic resilience of acute care facilities. The problem is framed in a broader societal context, from which is formulated a subproblem that can be addressed and quantified through a coordinated large-scale multidisciplinary earthquake engineering research effort. In this context, multidisciplinary earthquake and extreme events engineering is meant to be broader than engineering, although only the non-engineering issues that closely relate to the engineering ones are considered in this paper. The engineering tools that could result from an implementation of the concepts presented here could contribute and be integrated into decision support tools, which in turn could be used for the formulation of strategies and policies at a higher level. Hence focus on the subproblem described as part of this paper should not be viewed as a narrow engineering view of an important societal problem, but rather as an important building block required for the broader integrated tool that is ultimately needed. Finally, while focus here is on seismic resilience, it must be recognized that the presented concepts and formulations are equally applicable to other hazards. As

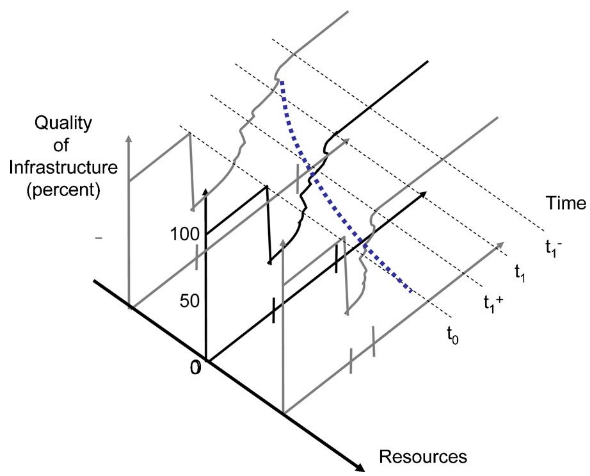

Figure 2. 3-D resilience concept (expanded in resourcefulness dimension).

such, the reader could substitute "extreme event engineering" for "earthquake engineering" throughout without loss of generality. For the sake of simplicity, focus remains on seismic resilience.

RESILIENCE CONCEPTS

Resilience for both physical and social systems can be further defined as consisting of the following properties:

- ***Robustness:*** strength, or the ability of elements, systems, and other measures of analysis to withstand a given level of stress or demand without suffering degradation or loss of function;
- ***Redundancy:*** the extent to which elements, systems, or other measures of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality;
- ***Resourcefulness:*** the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other measure of analysis. Resourcefulness can be further conceptualized as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources in the process of recovery to meet established priorities and achieve goals;
- ***Rapidity:*** the capacity to meet priorities and achieve goals in a timely manner in order to contain losses, recover functionality, and avoid future disruption

As such, the vertical and horizontal axes in Figure 1 address the ends of resilience, namely, robustness and rapidity. However, Figure 1 can be expanded three- and four-dimensionally to capture the means of resilience, namely, resourcefulness and redundancy. This is illustrated in Figures 2 and 3. In Figure 2, a third axis illustrates that added

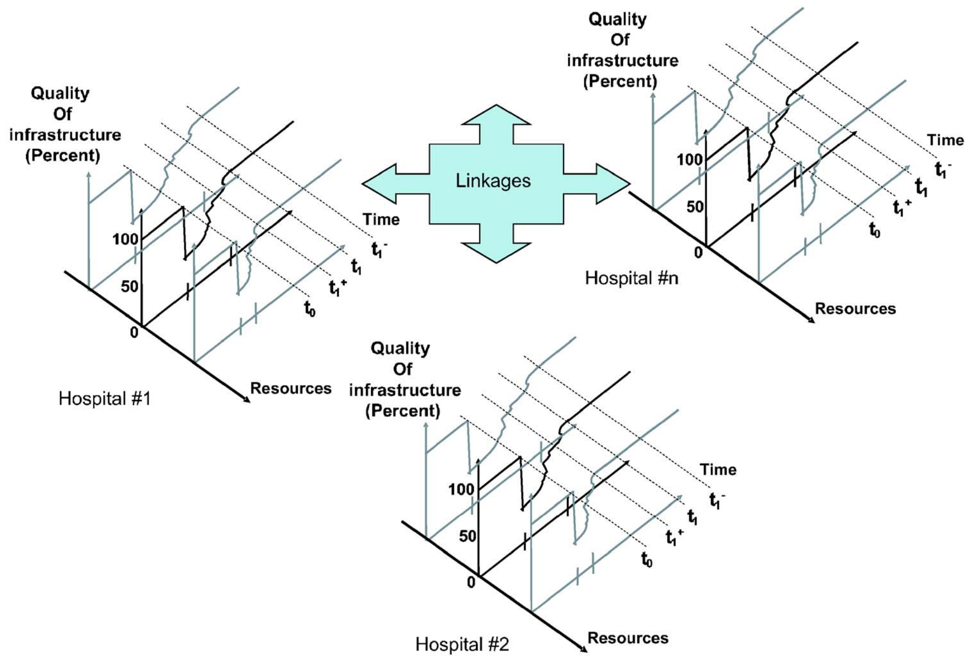

Figure 3. 4-D resilience concept (expanded with redundancy dimension).

resources can be used to reduce time to recovery beyond what is expected by the benchmark "normal" condition captured by Figure 1. In theory, if infinite resources were available, time to recovery would asymptotically approach zero. Practically, even in the presence of enormous financial and labor capabilities, human limitations will dictate a practical minimum time to recovery. This was demonstrated, for example, by the replacement of the Santa Monica freeway bridges following the 1994 Northridge earthquake in the Los Angeles region. The replacement of this critical infrastructure for the transportation network of the region was accomplished 2.5 months faster than originally projected, at a reported bonus cost of over $14 million paid to the contractor for early completion. Likewise in a less technologically advanced society, where resources are scarce, time to recovery lengthens, approaching infinity in the absence of any resources. Note that even in a "resourceful" society, the time to recovery after a disaster may be significantly longer than necessary due to inadequate planning, organizational failures/ inadequacies, or ineffective policies.

Figure 3 illustrates redundancy, the fourth dimension of resilience, by grouping multiple plots of the type shown in Figure 2. For example, while each individual 3-D resiliency space in Figure 3 could represent a single hospital, the collection of those represents the resiliency of all acute care facilities over a geographical area (whether or not these would be owned by a single health care provider just depends on which problem one wishes to model). As such, the seismic resiliency of a system of health care facilities could be assessed using that integrated framework, allowing one to investigate the impact of resource allocation policies with various emphases on robustness, rapidity, resourcefulness, and redundancy. One should note, however, that lifelines (such as the highway networks) provide linkages between hospitals, and that the seismic resiliency of lifelines also would play a role on the global resiliency of this distributed inventory of hospitals.

The measure of functionality can be expressed in more detailed way as

$$Q(t) = 100 - [L \cdot F \cdot \alpha_R] = 1 - [L(t_{0\mathrm{E}}) \cdot f_{\mathrm{rec}}(t, t_{0E}, T_{\mathrm{RE}}) \cdot \alpha_R] \tag{2}$$

where L (or more specifically $L(t_{0E})$) is the magnitude of loss function; F (or more specifically $f_{rec}(t, t_{0E}, T_{RE})$) represents the recovery function after the time of event occurrence t_{0E}, shaped according to the resources available and allocated during the recovery period, T_{RE}; and α_R is the functionality recovery factor. All the above functions vary between zero and one. The loss function is measured as the ratio of the actual loss, $L_{\mathrm{LS}}(t_{0E})$ (monetary, physical, technological, and informational) at an expected performance limit state (LS) in regard to the cost of maintaining the full performance measure (FP) expressed in the same units as the loss, expressed as

$$L(t_{0E}) = \sum_j [L_{\mathrm{LS},j}(t_{0E})/\mathrm{FP}] \cdot P_{\mathrm{LS},j}(R_j \geqslant \mathrm{LS}_j) \tag{3}$$

where $P_{LS}(R > LS)$ is the probability that the expectation R will exceed the performance limit state, LS. This probability function is also known as the fragility function (Shinozuka et al. 2000a, b). The summation in Equation 3 allows for the simultaneous consideration and combination of multiple performance limits or damage thresholds. This probability function, and its influence on the measure of functionality and resilience, is described in a later section.

RESILIENCE OF ACUTE CARE FACILITIES

Residents in seismic areas have expressed their strong expectation that acute care facilities be available and operational following an earthquake (Alexander 1996, Nigg 1998). As such, fulfillment of this expectation would significantly contribute to enhancing the seismic resilience of communities. California has already taken steps in that direction by enacting ordinance SB1953, which requires that acute care facilities be retrofitted by 2030 to a level that would allow them to be fully operational following an earthquake (Alesch and Petak 2004).

To quantify the seismic resilience of acute care facilities, the measure of functionality shown by the vertical axis of the resilience chart of Figure 1 must first be defined. This could be done in a number of different ways, depending on the type and range of mitigation actions that are contemplated.

A first option is to quantify quality of life as the percentage of healthy population (Figure 4). Using the total healthy population in the absence of an earthquake as a reference basis, and normalizing it to eliminate the effect of population growth over time, the horizontal line drawn at 100% on the vertical axis represents the healthy population

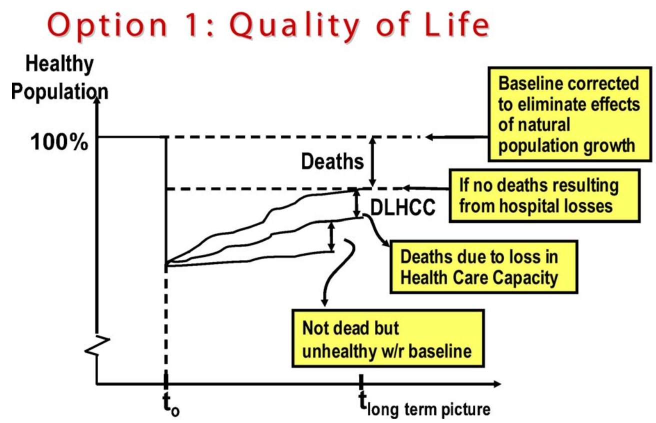

Figure 4. Quantification of seismic resilience of acute care facilities as percentage of healthy population.

that resides in an area that could be affected by a scenario earthquake. A first drop in population health would occur when individuals are killed by seismically deficient structures or from other causes during the earthquake (Peek-Asa et al. 1998). At a community scale, this number would not change whether hospitals are seismically retrofitted or not, except for those deaths that would have occurred in seismically deficient hospitals. Injuries suffered during the earthquake would account for the remaining reduction in the healthy population at time t_0. In the best scenario, in the absence of hospital losses, all these injuries would heal, and no more deaths would be added to the toll. Conversely, deaths due to loss in health care capacity (DLHCC) would occur, i.e., deaths would occur that could have been prevented if the health care system capability had not been reduced by the earthquake. Furthermore, a number of individuals, although alive, would likely suffer debilitating injuries or other scars/impairments forever as a result of being unable to receive appropriate treatment immediately following the earthquake, or due to loss of the specialized health care units they need for proper treatment of their chronic disease; these would translate into a marked loss of population health, even though not necessarily deaths.

This approach has the advantage that it seeks to quantify the impact of an earthquake on the health of a population, a true global societal measure of seismic resilience for a community, which is probably a significant measure for the purpose of policy making. However, it suffers a number of shortcomings. First, the quantification of unhealthy versus healthy may be difficult (although not impossible). Second, establishing how many deaths were directly or indirectly caused by the earthquake could be a challenge. Third, definition of the relevant geographical boundaries can be problematic given that the more wealthy and mobile segment of the population may find its health needs answered in other states (or countries). Fourth, development of accurate data may require substantial resources, requiring at least a coordinated effort among multiple government agencies. Furthermore, if one is interested in providing an engineering contribution to the

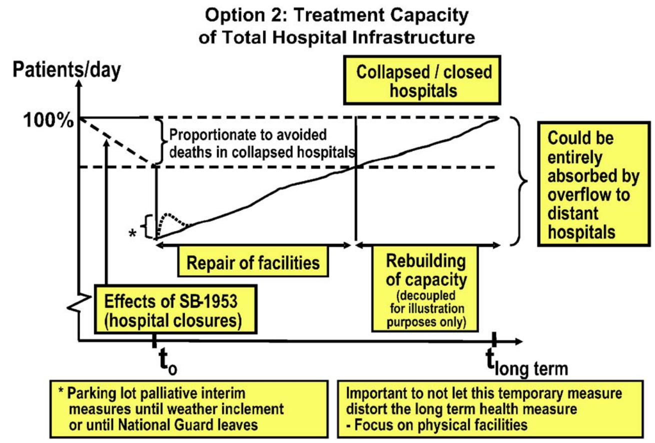

Figure 5. Quantification of seismic resilience of acute care facilities as patients/day treatment capacity of the total available hospital infrastructure.

quantification of resilience, in this broader context, it might not be possible to provide linkages between population health and integrity of the engineered infrastructure in the foreseeable future.

A second option focuses instead on relating the seismic resilience of acute care facilities to the number of patients/day that can be provided as a measure of the treatment capacity of the health care facilities (Figure 5). This could be done for a single institution or for all facilities across a geographical region. The following discussion focuses on the latter. This format can illustrate some short-term and long-term issues whose true impact has often been misinterpreted or exaggerated. For example, prior to an earthquake, the impact of SB1953 is shown (Figure 5) as resulting in the loss of some patients/day capacity, as some hospitals are expected to close rather than invest in meeting the seismic retrofit goals of that ordinance. However, since these would likely be facilities identified as suffering from (expensive to correct) severe seismic deficiencies, one could argue that this loss of capacity would have occurred anyhow at time t_0 (the time of an earthquake), but with severe collateral loss of lives. Also illustrated, following the major loss of patients/day capacity directly attributed to the earthquake, is the short burst of recovered patients/day capacity provided in the aftermath of the disaster. This is a consequence of the "parking-lot," "MASH"-like medicine often provided outside of hospital facilities that have suffered debilitating damage. This burst has typically been observed in warm-climate regions (Comm. on Pediatr. Emerg. Med. 1997) to treat earthquake-related injuries when transportation to a remote facility is difficult or impossible. This emergency setting usually lasts but a few days or weeks, and is not a viable solution for an earthquake that would occur in less accommodating weather or an urban setting (such as in New York City in January). In Figure 5, two distinct and concurrent recovery activities have been illustrated as sequential, namely, repair of capacity and re-building of capacity, the first dealing with replacement of capacity lost during the earthquake $\alpha_R = 1$ in Equation 2, the second related to increasing capacity to the level needed to service the needs of the population ($\alpha_R > 1$ in Equation 2).

The advantage of this second approach is that it focuses on the physical infrastructures and their ability to provide their intended function, which facilitates engineering quantification (Chang et al. 2002). This is not to imply that engineering issues are more important than the health issues described in the previous option, but only that this framework makes it possible for a coordinated earthquake engineering research effort to contribute in a focused and effective manner to the broader problem. While the engineering effort and resources needed to completely address all issues likely still require the concerted efforts of multiple government agencies and considerable funding, it is possible for smaller-scale engineering efforts to develop some of the tools and methodologies that could be integrated into decision support systems intended to consider multiple complex options related to seismic retrofit, and to identify the most effective allocation of limited resources. In this respect, these engineering quantification tools could be used to assess whether the seismic resilience is enhanced or not, i.e., whether a specific intervention (or set of interventions) effectively and significantly reduces the probability of a loss in patient/day capacity, assess if a specific overflow locally (due to loss of capacity) can be absorbed globally, and how long it might take to restore this capacity.

While this approach is more suitable for engineering quantification, it nonetheless remains a complex endeavor. For completeness and reliability of the results provided by a decision support system built upon a strong engineering basis (among many things), this quantification must encompass all equipment and units in a given hospital, as well as capture their interdependencies; whether some equipment would require replacement or repair following an earthquake is a priori difficult to quantify in engineering terms. Modeling of linkages between geographically distributed hospitals adds another layer of complexity, and for the sake of simplicity, one may have to assume that the performance of a network of hospitals can be established by simple aggregation of the performance of individual facilities. The probable error in this linear scaling is unknown at this time; although this may be a reasonable initial assumption, actual relationships will depend on the post-earthquake condition of the transportation network needed to establish effective linkages, which therefore requires knowledge of the fragilities of that network.

RESILIENCE OF STRUCTURAL AND NONSTRUCTURAL COMPONENTS

A first step toward the above objectives is the definition and quantification of engineering resilience. This is illustrated here by focusing on the resilience of structural and nonstructural components.

In light of the considerable uncertainties inherent to the field of earthquake or extreme-event engineering (in both the demands estimated through engineering seismology and the capacities that ensue from the nonlinear-inelastic seismic performance of the structure), the quantification of seismic resilience best proceeds through a probabilistic framework, as illustrated in Figure 6. For example, in that figure focusing on the single conceptual measure of structural integrity, three different levels of losses in in-

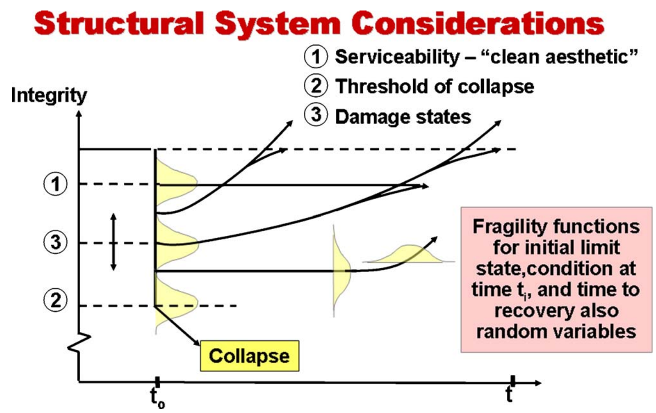

Figure 6. Probabilistic aspect of seismic resilience (structural integrity example).

tegrity are shown. A serviceability level is defined as a small loss in structural integrity, a point where only aesthetic damage is observed, not having any significant impact on structural response. A collapse level is defined as the maximum loss of integrity that can be sustained prior to collapse; the downward arrow indicates that rapidly cascading losses accumulate to collapse once that level is reached, and no sustainable level of integrity can exist below the threshold of incremental collapse. Other resilience curves are shown to represent various structural integrity conditions between the serviceability and collapse levels, and the fact that a proportional coupling often (but not always) exists between the time to recovery and the initial loss of structural integrity. For example, cosmetic damage is easier to repair than severe damage to structural elements. It is also illustrated that over time, structural integrity could return to the initial pre-earthquake or extreme-event condition, to less than this condition (e.g., cracking in some structural element may never be repaired), or to above this condition if the structure is repaired to a superior seismic performance level. The bell curves in that figure also show that each of these integrity levels is a random variable, as well as the time to recovery. The drawback of Figure 6, however, is that it does not explicitly spell out the specific limit states that, when violated, lead to this loss of structural integrity, nor does it show a way to quantify the probability that these limit states are exceeded. The vertical axis in Figure 6 also needs to be defined in a manner allowing quantifying structural and nonstructural resilience (i.e., engineering resilience here). Cases with linear-elastic and nonlinear-inelastic structural response are both considered in the following to show how a complete set of structural and nonstructural resilience curves can be developed in each case.

SOMBRERO CONCEPT IN OLE

One way to achieve quantification of engineering seismic resilience is through the concept of Sliding an Overlaid Multidimensional Bell-curve of Response for Engineering Resilience Operationalization (SOMBRERO), using, for example, an Orthogonal Limit-space Environment (OLE). Therefore, for the purpose of this discussion, the prob-

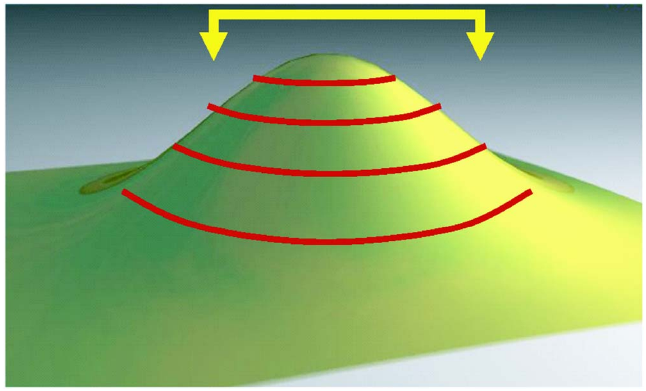

Figure 7. Definition of point of view and isoprobability contours of two-dimensional bell curve.

ability distribution surface (i.e., 3-D "bell curve") schematically shown in Figure 7 is used. Viewed from above, the surface can be expressed by isoprobability contours, as shown in Figure 8. Spherical contours are used here for expediency. Floor pseudo-accelerations (PSA floor) and interstory drifts (S_d floor) express the OLE, with specific structural and nonstructural limit states shown by dotted lines; for the former, a serviceability limit state (cracking of concrete structural elements, for example) and a collapse limit state are indicated. Deterministic limit states are used here, but do not need to be (Cimellaro et al. 2005, 2006; Reinhorn et al. 2006). Floor acceleration and interstory drift are therefore the structural response probabilistic parameters considered here by the SOMBRERO concept. As graphically shown in Figure 8, the probability that response exceeds a specific limit state can be directly calculated from the volume under the surface distribution exceeding the specified limit. For a given structural response, nonstructural retrofit measures that would allow the nonstructural components to resist greater floor accelerations (i.e., move up the acceleration limit state dotted line in Figure 8) would directly translate into a smaller volume under the probability distribution surface, and thus a smaller probability of exceedance of the limit state. The same observations could be made for any limit state along the S_d-floor axis. However, modifications to the structural system change the probable structural response, which is equivalent to sliding the multidimensional bell curve within the OLE (i.e., moving along the dotted arrows in Figure 8). For example, stiffening the structural system in a manner that reduces interstory drifts would move the response surface to the left of the OLE of Figure 8, but could also move it upward or downward, depending on the initial structural period (although the former is more likely). Structural damage during an earthquake would weaken the structure, leading to increased deformations, but somewhat lower accelerations, moving the response surface toward the right and possibly downward (solid arrow in Figure 8), resulting in greater intersection with the drift-controlled limit states, mean-

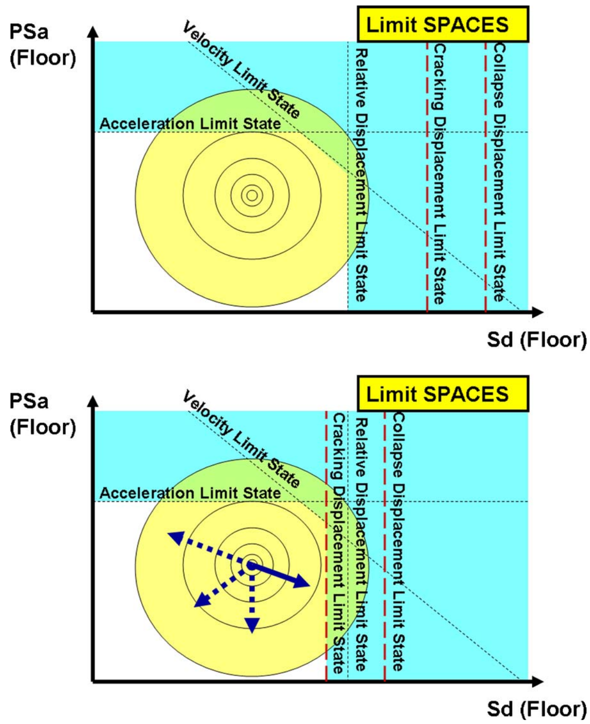

Figure 8. Probability that response exceeds limit space: (a) nonstructural limit states reached prior to structural limit states; and (b) different sequence of limit states.

ing increased probability of violating the limit state should another identical earthquake occur. Note that the shape or width of the probability distribution surface may also change for each case considered.

The mathematical formulation of the probability of exceedance for a two-dimensional limit state and response distributions is expressed as follows (Cimellaro et al. 2005, 2006; Reinhorn et al. 2006):

$$P_{\mathrm{LS}} = \lim_{N_{\mathrm{TE}}\to\infty} \left\{ \frac{\mathrm{N_R}\left[\left(\dfrac{R_a}{a_{\mathrm{LIM}}}\right)^{N_a} + \left(\dfrac{R_d}{d_{\mathrm{LIM}}}\right)^{N_d} > 1\right]}{N_{\mathrm{TE}}} \right\} \tag{1'}$$

where N_R is the number of responses that exceeds the performance limit defining the level of functionality in term of acceleration limits (a_{Lim}) and deformation limits (d_{Lim}); N_{TE} is total number of responses; N_a, N_d are interaction factors determining the shape of the limit state surface; R_a is the maximum acceleration response; R_d is the maximum displacement response; a_{Lim} is the acceleration limit threshold; and d_{Lim} is the displacement limit threshold. This equation relates the number of responses, N_R, which exceed the surface bounded by the numerator's function representing the multidimensional per-

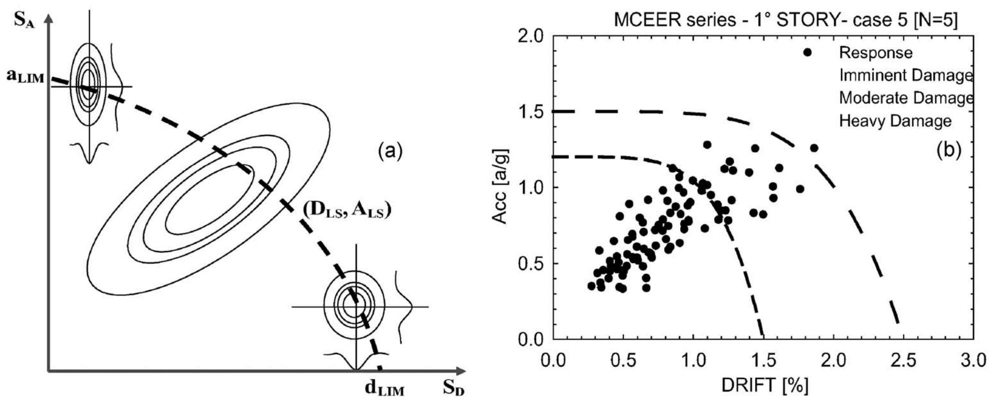

Figure 9. Response function and limit states in actual building: (a) response and limit state distributions, and (b) actual data.

formance limit state, to the total number, N_{TE}, of possible responses during the life cycle of the structure. This formulation is an extension of Hwang et al. (2000). Actual response function and limit states are shown in Figure 9.

CASE 1: LINEAR-ELASTIC STRUCTURAL RESPONSE

Quantification of the seismic resilience curve is first presented for the case of linear-elastic structural response. For this and all subsequent cases considered, the vertical axis of the resilience curves is in terms of "investment value" in the structural system, or the nonstructural system. Figure 9a illustrates that there is no structural loss (i.e., no drop in the value of structural investment) when the structure remains elastic. As such, from the SOMBRERO concept, this is equivalent to having no significant intersection between the probabilistic response surface and the structural limit states in Figure 8. However, such intersection exists in the OLE for the nonstructural components, and the magnitude of this intersection (i.e., probability of exceeding the limit space) can be calculated, and is expected to increase as a function of the earthquake return period. Figure 9b expresses the resulting probability of exceeding the limit space as a function of the earthquake hazard (itself expressed in probability of exceedance over 50 years, in a manner compatible with code documents—50%, 10%, and 2% probability of exceedance shown along the hazard axis for illustration purposes approximately correspond to earthquakes having return periods of 100, 500, and 2,500 years). The probable nonstructural loss, L_{NSL}, can be expressed by the product of the probability of exceeding the performance limit state, P_{LS}, and of the value of replacing the damaged nonstructural component versus its initial investment, FP as indicated by Equation 3. In this case, which focuses on nonstructural investment, FP is expressed as NS_{INV}. For the probable exceedance of the limit space shown in Figure 10c for a design level corresponding to a 500-year return period, Figure 10b shows the resulting nonstructural resilience curve,

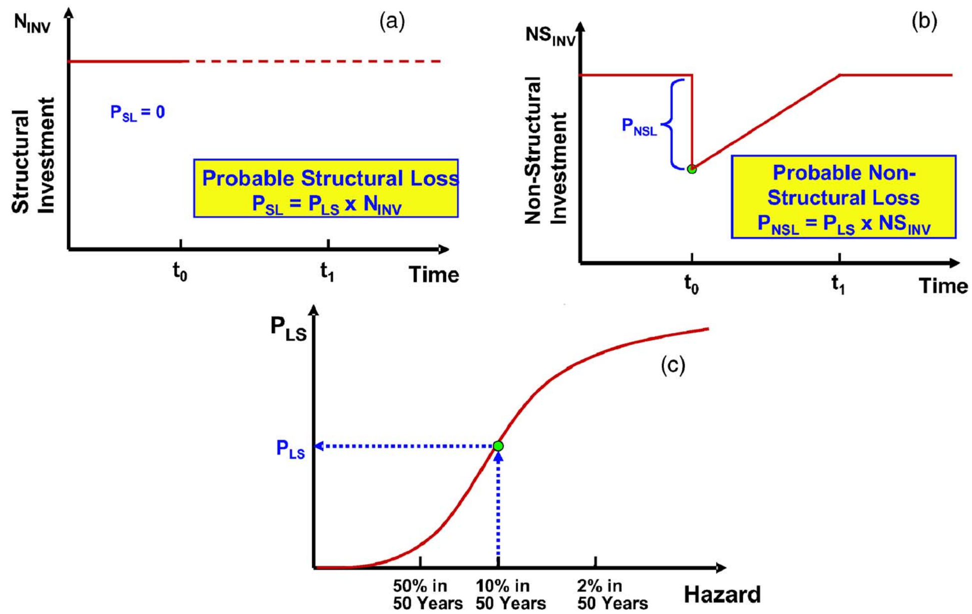

Figure 10. Probable nonstructural loss in case of linear-elastic structural response: (a) structural resilience curve; (b) nonstructural resilience curve; and (c) probability of exceeding limit state.

with the probable nonstructural losses at time t_0. The time at full recovery to pre-earthquake conditions, t_1, is entirely related to repair of nonstructural damage.

CASE 2: NONLINEAR-INELASTIC STRUCTURAL RESPONSE

Quantification of the seismic resilience curve for the case of nonlinear-inelastic structural response differs from the previous case by the presence of a structural loss (i.e., a drop in the value of structural investment due to damage) measurable from the SOMBRERO concept since there is now a quantifiable intersection between the probabilistic response surface and the structural limit states in Figure 8. As for the previous case, the probability of exceeding the limit space can be calculated and generally increases as a function of the earthquake return period. Figure 11b expresses the resulting probability of exceeding the limit space, P_{LS}, as a function of the earthquake hazard, and Figure 11a the corresponding probable loss in the structural investment, L_{LS}. In this case, which focuses on the structural investment, FP is taken as N_{INV}. As indicated earlier, as a result of damage, the probabilistic response surface has displaced within the OLE of Figure 8 to a new position the instant after time t_0 (labeled t_0^+). If another earthquake were to occur at time t_0^+, the probability of exceeding the limit state would be significantly greater (as shown in Figure 11d), and a further loss in the structural investment (possibly to collapse) would occur (Figure 11c).

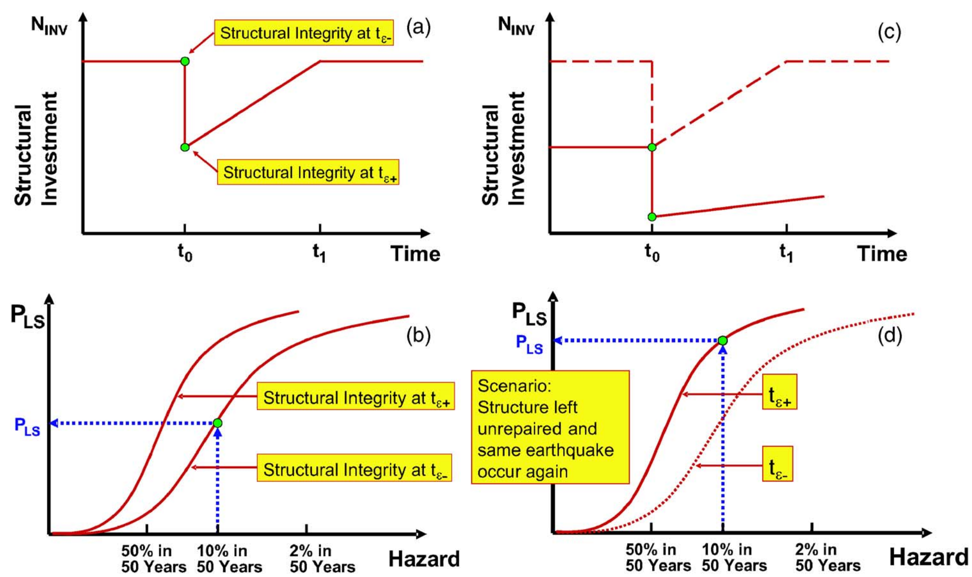

Figure 11. Case of nonlinear structural seismic response: (a) structural resilience curve and corresponding loss in structural integrity; (b) probability of structural loss before earthquake; (c) new structural resilience curve if structure left unrepaired; and (d) probability of failure upon repeat of earthquake.

The probable nonstructural loss would be calculated as before, with the only difference that if the same earthquake were to re-occur at time t_0^+, the probability of exceeding the nonstructural limit space could increase or decrease, depending on the type of nonstructural components, and the extent of structural damage (e.g., a "softer" damaged structure might undergo lower floor accelerations but greater floor interstory drifts).

Figures 12a and 12b illustrate how structural repairs (arbitrarily shown at equal time increments here) progressively shift the curve of probable losses back to the original condition that existed at the instant before t_0 (thus equal to the condition at t_1). This requires a financial investment and one could quantify the cost required to shift from one probabilistic curve to another (unlikely to be a linear relationship). The rate of repair also provides a measure of the rapidity dimension of the resilience curve. Note, as shown in Figures 12c and 12d, that it is possible to increase the value of the investments to above the pre-earthquake condition, enhancing seismic resilience by reducing the probability of losses in a future repeat of the same earthquake.

The benefit of retrofitting prior to an earthquake can also be assessed and quantified using the resiliency concept presented in Figures 10 and 11. To illustrate how this is achieved, the fragility curves at times t_0^- and t_0^+ of Figure 11a will be used. It is assumed here, for convenience, that the relativity of this pair of fragility curves for a given structure remains the same, and that seismic retrofit prior to an earthquake is equivalent to sliding of the fragility curves along the horizontal axis such that a greater earthquake is

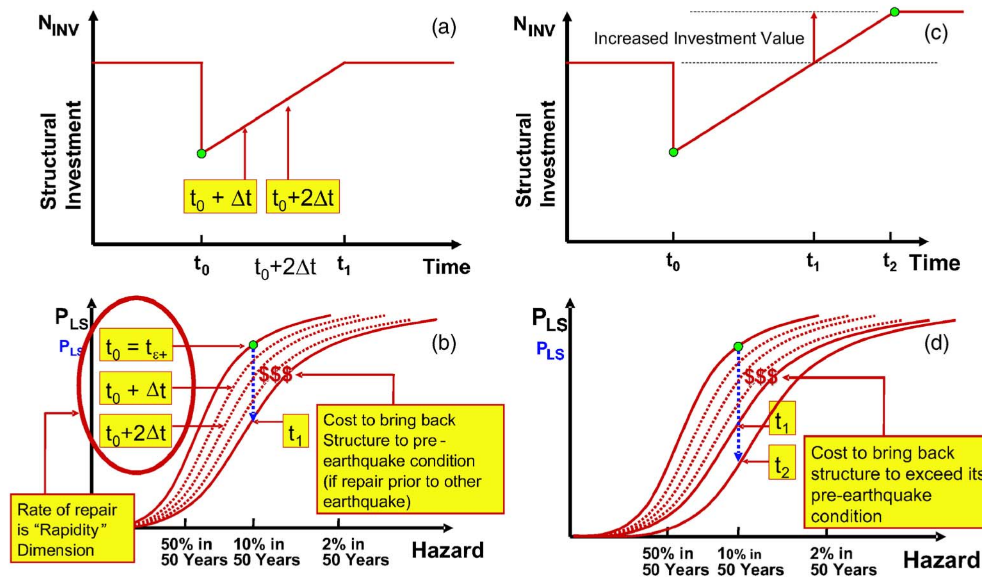

Figure 12. Case of nonlinear structural seismic response: (a) improvement in structural resilience as structure is repaired over time; (b) corresponding reduction in probability of structural losses; (c) increased resiliency to above pre-earthquake condition; and (d) corresponding improvement in probability of structural losses.

required after retrofit to produce the same probable loss of the structural investment. Failing the availability of a theory to quantitatively substantiate this assumption of constant relationship between pairs of fragility curves for a given structural condition, this will be referred to here as the "Reinhorn-Bruneau Sliding Pair of Fragility Curves" assumption. As shown in Figure 13, once the structure has been retrofitted, the investment in the structural system has been increased, which translates into the elevated resilience curve of Figure 13b. Furthermore, should the same expected earthquake occur (with a return period corresponding to 10% change of exceedance in 50 years for the example in Figure 13a), the probable loss in structural investment due to damage is also reduced, as shown by the corresponding drop between time t_0^- and t_0^+ in Figure 13b.

The corresponding impact of either structural damage or seismic retrofit on the fragility and resilience curves of nonstructural component for the case of nonlinear structural seismic response and nonretrofitted nonstructural components is somewhat unknown. For example, structural damage could result in a more flexible structure, which would have greater displacements but smaller floor accelerations upon a recurrence of the same earthquake at time t_0^+. The total probability of losses in nonstructural component would depend on the SOMBRERO in the OLE. In Figure 14a, for the case of structural damage due to an earthquake at time t_0^-, it is assumed that the resulting probability of losses would increase, with a corresponding greater probable loss of the nonstructural investment, possibly up to total loss, as shown in Figure 14b.

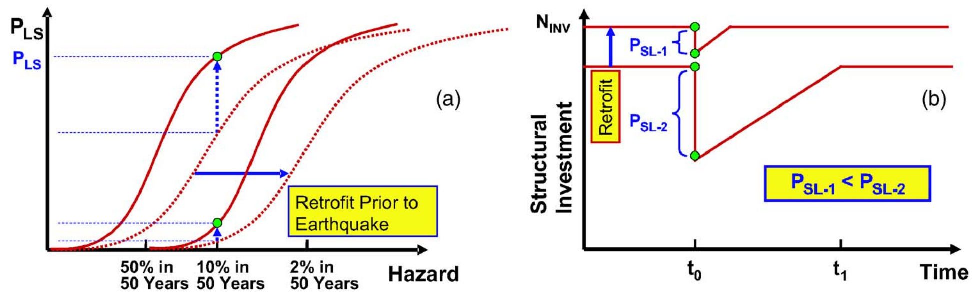

Figure 13. Case of nonlinear structural seismic response: (a) Bruneau/Reinhorn assumption of sliding proportional fragility curve sets; and (b) enhancement of resilience curve consequently to reduced probability of losses due to seismic retrofit prior to earthquake.

INTEGRATING COMPONENT RESILIENCE

Enhancing the seismic resilience of acute care facilities depends not only on the integrity of structural and nonstructural component, but also on many other factors, resulting in "multivariable" fragility dependencies. To establish the relationships between various engineering integrity measures and loss of patients/day capability requires integrating (quantitatively) component fragilities (including nonstructural, structural, geotechnical, etc.) into a system resilience (using the same units for vertical axis as presented in the first part of this paper).

A "road map," such as the one shown in Figure 15, is helpful to show the steps needed to quantify and enhance the seismic resilience of acute care facilities, and to serve as a tool to identify and focus research activities toward this objective, by listing the steps toward the objective, and the essential dependencies. The road map of Figure 14 emphasizes that seismic resilience may be compromised by failure of both engineered and non-engineered systems. It also conceptually illustrates the probabilistic fragility framework that must be integrated to quantify seismic resilience of acute care facilities, and where interventions can be made to enhance this resilience.

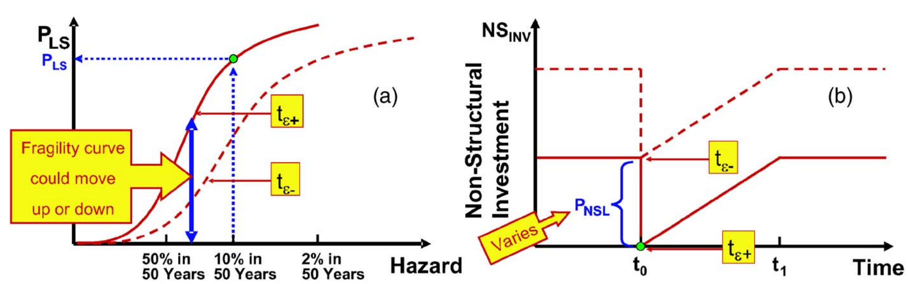

Figure 14. Case of nonlinear structural seismic response: (a) probability of nonstructural losses, and (b) corresponding shifts in nonstructural seismic resilience curve.

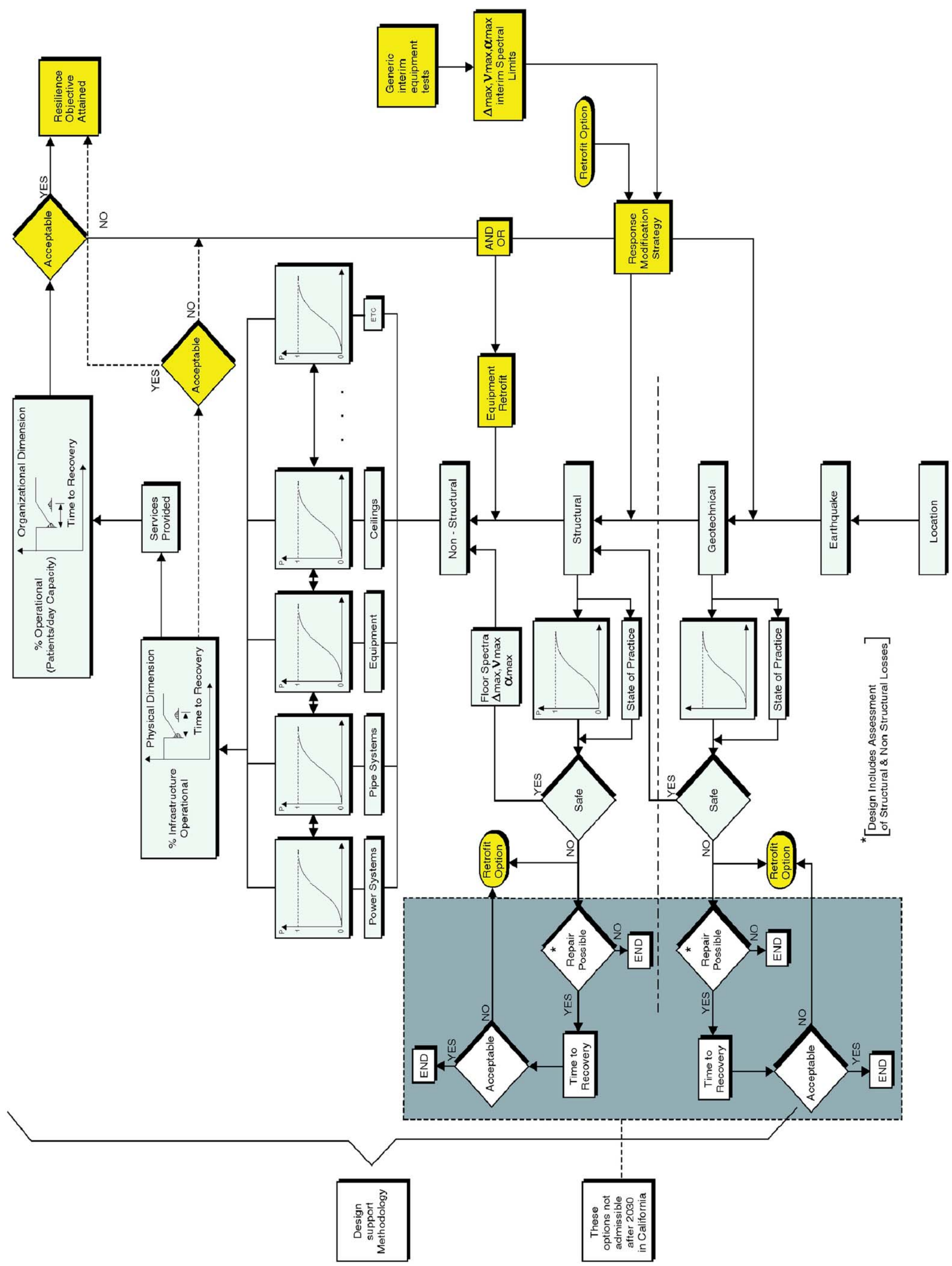

Figure 15. Flow chart of procedure to achieve seismic resilience for a single hospital.

As shown in Figure 15, a first interim quantification of resilience is possible at the physical dimension level. From there, social science research input is needed to generate the knowledge to elevate the resilience quantification to the organizational dimension level by translating the physical system resilience into operational consequences.

The road map also emphasizes the pivotal need for information on the fragility of nonstructural building components to achieve the research objectives through the above methodology. Achieving a given target seismic resiliency for acute care facilities requires the harmonization of the performance levels between structural and nonstructural components. Even if the structural components of a hospital building achieve an immediate occupancy performance level after a seismic event, failure of architectural, mechanical, or electrical components of the building can lower the seismic resiliency of the entire building system. Furthermore, the investment in nonstructural components and building contents for the hospital is far greater than that of structural components and framing (Taghavi and Miranda 2003). Therefore, it is not surprising that in many past earthquakes, losses from damage to nonstructural building components exceeded losses from structural damage. Clearly, the development of equipment fragilities (which is often not within the purview of academic research, but rather the responsibility of industry) is needed most urgently. Availability of such calibrated and reliable data, integrated into a decision support system that would model the dependencies illustrated in Figure 15, would allow decision makers to achieve reliable decisions based on optimization of resources targeted to enhance seismic resilience of an existing hospital or ensemble of geographically distributed such facilities (Alesch et al. 2003).

RESILIENCY NONLINEARITY

While the resiliency framework is a useful and valuable concept, the single number provided by the area defined by Equation 1 as a measure of the lack of resilience should be used with care. For a power-distribution grid, the units of that area could be kW* days, and for hospitals patient/days (Shinozuka et al. 2004). If this definition for the lack of resilience was exact, similar areas would correspond to the same lack of resilience, irrespectively of the shape of that shaded area. However, as revealed by informal surveys, this does not appear to be the case. The two graphs in Figure 16 illustrate this, whereas a total loss for 2 days is compared to a 10% loss for 20 days. Even though the areas are the same, the two events are certainly not perceived to have the same impact. While one could immediately contemplate using different weighing factors along each axis to handle this situation, a difficulty arises as the event perceived to have the greatest impact varies depending on the audience. For service providers, the preferred scenario tends to be the one in which most customers are not adversely affected by the disaster, at the cost of loss of service to a small base of customers. However, the recipients of services seem to prefer the "equitably shared hardship" scenario in which all severely suffer but for a shorter time period, as individuals are apparently most concerned with the possibility of being one of the "lucky" few left without service for a long period of time (these two diametrically opposed positions were identified in discussions with various stakeholders). This is not to imply that the resiliency framework is invalid, but rather that

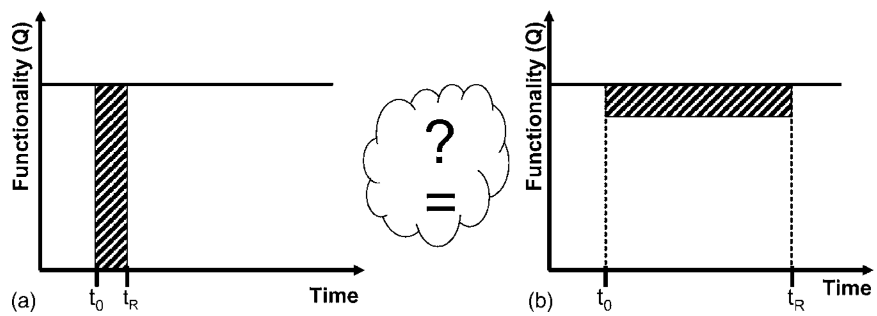

Figure 16. Nonlinearity of resilience concept.

the single number that defines lack of resilience is nonlinear and it might need to be calibrated differently to address the specific needs of different audiences.

In some cases, however, the trade-offs are not so polarized. For example, for hospitals, one could argue that, for a given amount of resources (resourcefulness and redundancy), initial loss of capacity and time to recovery are linked; in other words, it may take longer to restore a system to its original capacity if the initial loss is more significant. As such, it could be argued that investing in limiting initial losses might, in some instances, be the preferred approach to enhance seismic resilience as it automatically translates into a consequent reduction in time to recovery; it is an investment that pays benefits along both axes.

RESILIENCY NONLINEARITY TARGETS

A possible final quantification of seismic resiliency assessment could be stated in the following format, which may be suitable for some stakeholders: "There is a 95% chance that 80% of hospitals can operate at 90% of their capacity within 5 days following an earthquake." This is a statement that addresses a measure of loss of capacity (90% of capacity), an assessment of time to recovery (within 5 days), integration over a geographically distributed system as an option (80% of hospitals), and a statement on the reliability of this quantification (95% chance, which alternatively could be worded as "this assessment is correct 19 times out of 20," a format commonly used by the media in presenting survey data to the public).

At this time, communities cannot articulate such resiliency objectives, as they cannot operate at this level of sophistication. This is partly because the tools to support such statements do not yet exist. Research is most needed to develop such tools, which decision makers will then be able to use to formulate the numbers themselves. However, in formulating policies anchored in quantitative resiliency targets, one must recognize that resiliency targets, while important objectives, are not to be taken as absolutes. For example, if a target seeks 85% of patients/day capability, achievement of only 84% following an earthquake should not be considered a policy failure. Likewise, consistent with the above discussion, resiliency targets may not be linear in their consequences.

First, achieving only 42.5% of patients/day capability may actually be a lot worse than "half-as-bad" as 85%, as one might expect that the degradation of public health could accelerate epidemically with progressively lower patients/day capacity. Second, as described above, stakeholders' perceptions are significant in determining whether 42.5% capacity in 5 days, instead of 85% in 5 days, is better or worse than 85% in 10 days.

This again points to the need for a quantitative probabilistic framework and tools anchored in rigorous engineering procedures to help guide decision makers in their consideration of various policies, rather than to focus on developing numerical values in a one-size-fits-all approach.

In the end, willingness to invest in pre-earthquake mitigation measures aimed at reducing seismic resilience is intrinsically tied to the earthquake risk as perceived by the stakeholders. To be extreme, one could argue that this fundamental rule is truly embodied in the psyche of human nature, and consequently in the civil/construction engineering field, since its basic premise is taught at an early age by the story of the three little pigs. Quantitative resiliency measures, integrated into decision support tools, will help respective stakeholders better understand their exposure and options by providing well-anchored data from which they can reassess their perceptions.

PERFORMANCE-BASED DESIGN WITHIN THE RESILIENCE FRAMEWORK

The seismic resilience framework described above is not at odds with the performance-based design approach being developed as part of the ATC-58 process (unpublished draft report ATC 2005). The resilience approach considers the losses and loss recovery over time, with loss functions reported in engineering and economical terms, as well as in terms of functionality during and after an extreme event. While some components of "loss" used in the quantification of resilience are related to the "death, dollars, and downtime" approach of ATC-58, other aspects of "loss" are related to various levels of functionality within either the recovery period, a more global time frame of the system's design lifecycle, or another time frame deemed significant to specific communities and stakeholders (as well as policy makers). In other words, the resilience formulation introduces the effects of response, recovery, and retrofit in the aftermath of the seismic event as parameters of the functionality losses (monitored and updated over time), which influence structural and socioeconomic systems beyond the performance defined by ATC-58. It can also capture interdependencies of diverse systems as they impact global resilience objectives.

The approach promoted by ATC-58 has been under development for over a decade and is consequently conceptually more familiar to practicing engineers (although not completed or implemented yet). However, the seismic resilience approach, still in its development stages, is more comprehensive, relating functionality, safety, and socioeconomic impacts over time, which is relevant to the design engineer as well as the other stakeholders of the socioeconomic environment. The performance-based design approach of ATC-58 provides a process to reach initial targets of "functionality" valid in achieving the comprehensive resilience of structures. As such, the ATC-58 development is a critical subset element of the resilience framework.

CONCLUSIONS

The concept of seismic resilience, and a methodology describing how it can be framed and quantified for acute care facilities has been presented. Relationships between seismic performance, fragility curves, and resilience functions have been described. The close interdependency of structural and nonstructural resilience has been illustrated for systems having either linear-elastic or nonlinear-inelastic structural behavior. The methods proposed to quantify resilience can be useful to provide a comprehensive understanding of damage, response, and recovery. The resilience functions explain quantitatively and qualitatively the time variation of damage as well as its relationship to response and recovery. This framework to quantify resilience can also help the decision process towards providing effective seismic mitigation, or the planning process to efficiently guide response and recovery. It also shows how the recognized components of resilience, such as fragility, performance limit states, and response can be effectively influenced by response modification or capacity enhancements.

REFERENCES

Alesch, D. J., Dargush, F. G., Grigoriu, M., Petak, W. J., and von Winterfeldt, D., 2003. *Decision Models: Approaches for Achieving Seismic Resilience*, MCEER Research Progress and Accomplishments 2001–2003, Report MCEER-03-SP01, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York, Buffalo, NY.

Alesch, D. J., and Petak, W. J., 2004. Seismic retrofit of California hospitals: Implementing regulatory policy in a complex and dynamic context, *Nat. Hazards Rev.* **5** (2), 89–96.

Alexander, D., 1996. The health effects of earthquakes in the mid-1990's, *Disasters* **30** (3), 231–247.

Applied Technology Council (ATC), 2005. *Guidelines for Seismic Performance Assessment of Buildings*, ATC-58 25% Draft, http://www.atcouncil.org/pdfs/ATC-58-25percentDraft.pdf

Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., and von Winterfeldt, D., 2003. A framework to quantitatively assess and enhance the seismic resilience of communities, *Earthquake Spectra* **19** (4), 733–752.

Bruneau, M., and Reinhorn, A., 2004. Seismic resilience of communities—Conceptualization and operationalization, *Proceedings, International Workshop on Performance-based Seismic-Design, Bled, Slovenia, June 28–July 1*.

Chang, S. E., Svekla, W. D., and Shinozuka, M., 2002. Linking infrastructure and urban economy—Simulation of water disruption impacts in Earthquakes, *Environ. Plan. B: Plan. Des.* **29** (2), 281–301.

Cimellaro, G., Reinhorn, A. M., Bruneau, M., and Rutenberg, A., 2006. *Multidimensional Fragility of Structures—Formulation and Evaluation*, Technical Report MCEER-06–0002, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York, Buffalo, NY.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M., 2005. Seismic resilience of a health care facility, in *Proceedings of the 2005 ANCER Annual Meeting, Session III, November 10–13, Jeju, Korea*, Paper No. 3.

Committee on Pediatric Emergency Medicine, 1997. The pediatrician's role in disaster preparedness, Pediatrics, American Academy of *Pediatrics* **99** (1), 130–133.

Hwang, H., Jernigan, J. B., and Lin, Y., 2000. Evaluation of seismic damage to Memphis bridges and highway systems, *J. Bridge Eng.* **5** (4), 322–30.

Nigg, J. M., 1998. Empirical findings based on research conducted under NSF Grant No. CMS-9812556, *Perceptions of Earthquake Impacts and Loss-Reduction Policy Preferences among Community Residents and Opinion Leaders*, J. M. Nigg, principal investigator.

Peek-Asa, C., Kraus, J. F., Bourque, L. B., Vimalachandra, D., Yu, J., and Abrams, J., 1998. Fatal and hospitalized injuries resulting from the 1994 Northridge earthquake, *Int. J. Epidemiol.* **27**, 459–465.

Reinhorn, A. M., Cimellaro, G., and Bruneau, M., 2006. Quantification of resilience of structure subjected to extreme events, *J. Struct. Eng.* (under review).

Shinozuka, M., Feng, M. Q., Kim, H., and Kim, S., 2000a. Nonlinear static procedure for fragility curve development. *J. Eng. Mech.* **126** (12), 1287–95.

Shinozuka, M., Feng, M. Q., Lee, J., and Naganuma, T., 2000b. Statistical analysis of fragility curves, *J. Eng. Mech.* **126** (12), 1224–1231.

Shinozuka, M., Chang, S. E., Cheng, T. C., Feng, M., O'Rourke, T., Saadeghvaziri, M. A., Dong, X., Jin, X., Wang, Y., and Shi, P., 2004. *Resilience of Integrated Power and Water Systems*, MCEER Research Progress and Accomplishments, Report MCEER-04-SP01, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York, Buffalo, NY., 252 pp.

Taghavi, S., and Miranda, E., 2003. *Response Assessment of Nonstructural Building Elements*, Report PEER 2003/05, Pacific Earthquake Engineering Research Center, University of California, Berkeley, 96 pp.

Whitman, R. V., 1973. *Damage Probability Matrices for Prototype Buildings*, Massachusetts Institute of Technology, Department of Civil Engineering, Research Report R73–57, Cambridge, MA.

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