# Overview of the Resilience Concept

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## ABSTRACT

The seismic resilience of a system can be achieved by reducing its probability of failure during an earthquake, as well as reducing the consequences from such failures and the time to recovery.  Within the perspective of this framework, this paper explores the physical resilience of facilities. Quantification of resilience is first approached from the broader societal context, from which the engineering sub-problem is formulated as an important building block of the integrated tool ultimately needed.  Quantification of physical resilience for facilities relates the probability of exceeding floor accelerations and inter-story drifts within a specified limit space, for the structural and non-structural performance.  Non-linear 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.

## 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 (re-establish normal performance), as described in Bruneau et al. (2003).  More specifically, a resilient system is one that shows:
1. Reduced failure probabilities,
2. Reduced consequences from failures, in terms of lives lost, damage, and negative economic and social consequences,
3. 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% 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 an example, in Figure 1).  Restoration of the

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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:

$$R=\int_{t_o}^{t_1}\left[100\text{-}Q(t)\right]dt \qquad\qquad [1]$$
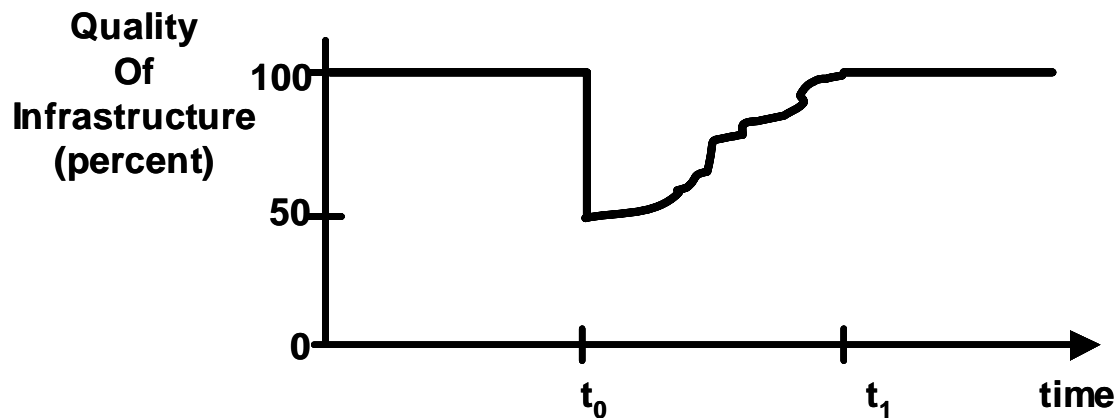


Figure 1. Schematic representation of seismic resilience concept (Bruneau et al. 2003)

Much research is needed to quantify resilience, particularly for some type of critical facilities. 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 facilities. 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 sub-problem 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.

### 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 threatens to disrupt some element, system, or other measures 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 in 3-D and 4-D to capture the means of resilience, namely resourcefulness and redundancy. This is illustrated in Figures 2 and 3. In Figure 2, it is illustrated, by a third axis, that added 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.
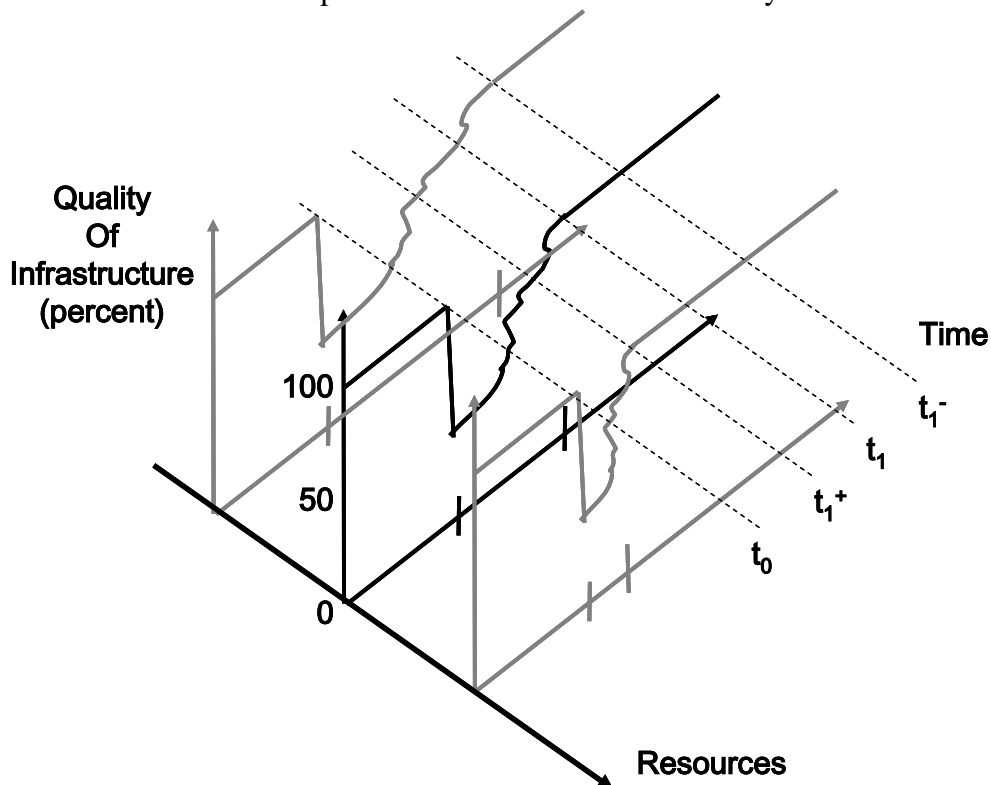


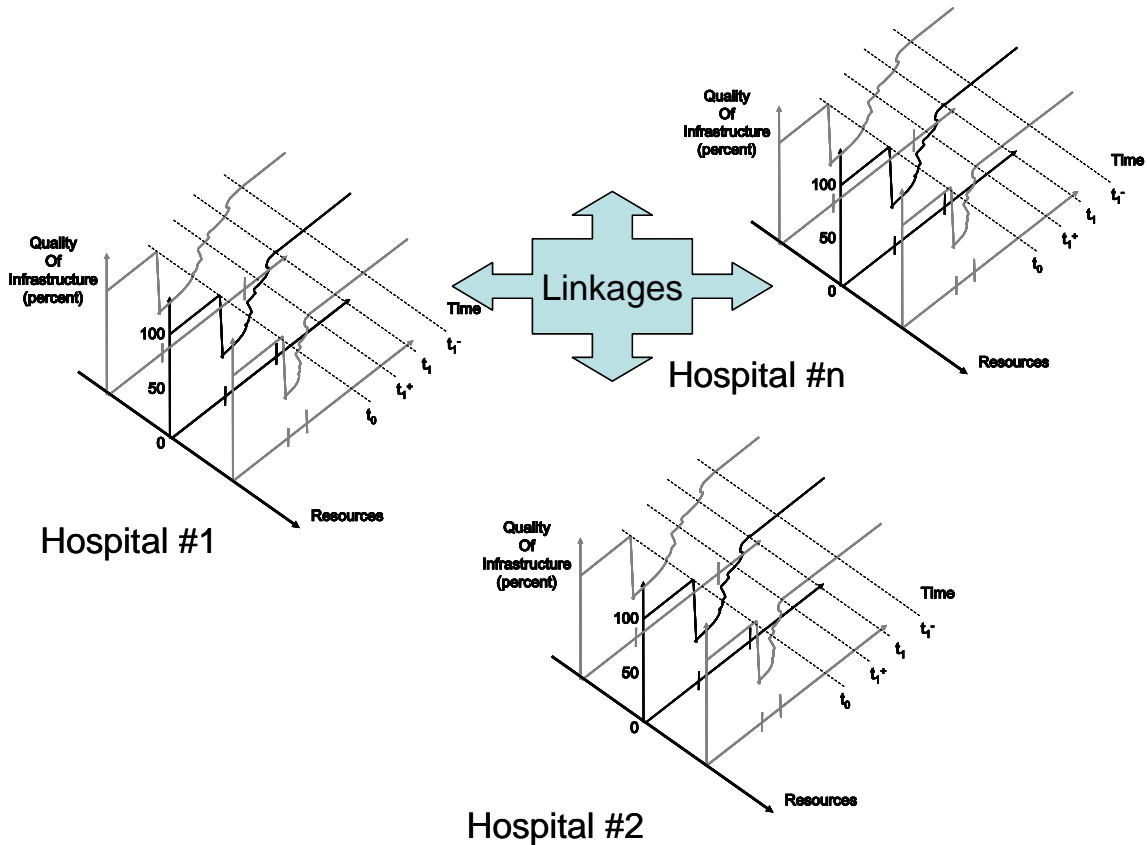Figure 2. 3-D resilience concept (expanded in resourcefulness dimension)

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

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 3D 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.

### Resilience of Structural and Non-Structural Components

### 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). A probability distribution surface, viewed from above, can be expressed by isoprobability contours, as shown in Figure 4. Spherical contours are used here for expediency.

Floor pseudo-accelerations (PSA floor) and inter-story drifts ($S_d$ floor) express the OLE, with specific structural and non-structural 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 need not be (Cimellaro et al, 2005; 2006; Reinhorn et al. 2006). Floor acceleration and inter-story drift are therefore the structural response probabilistic parameters considered here by the SOMBRERO concept. As graphically shown in Figure 4, 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, non-structural retrofit measures that would allow the non-structural components to resist greater floor accelerations (i.e., move up the acceleration limit state dotted line in Figure 4) 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 4). For example, stiffening the structural system in a manner that reduce inter-story drifts would move the response surface to the left of the OLE of Figure 4, and 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 4), resulting in greater intersect with the drift-controlled limit states, meaning 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.

**Case of Non-linear Inelastic Structural Response**

Quantification of the seismic resilience curve for the case of non-linear inelastic structural response is measurable from the SOMBRERO concept from the quantifiable intersect between the probabilistic response surface and the structural limit states in Figure 4. The probability of exceeding the limit space can be calculated, and generally increases as a function of the earthquake return period. Figure 5b expresses the resulting probability of exceeding the limit space, $P_{LS}$, as a function of the earthquake hazard, and Figure 5a expresses the corresponding probable loss in the structural investment, $L_{LS}$. In this case, focus is on the structural investment $N_{INV}$. As indicated earlier, as a result of damage, the probabilistic response surface has displaced within the OLE of Figure 4 to a new position the instant after time $t_o$ (labeled $t_o^+$). If another earthquake was to occur at time $t_o^+$, the probability of exceeding the limit state would be significantly greater (as shown in Figure 5b), and a further loss in the structural investment (possibly to collapse) would occur.
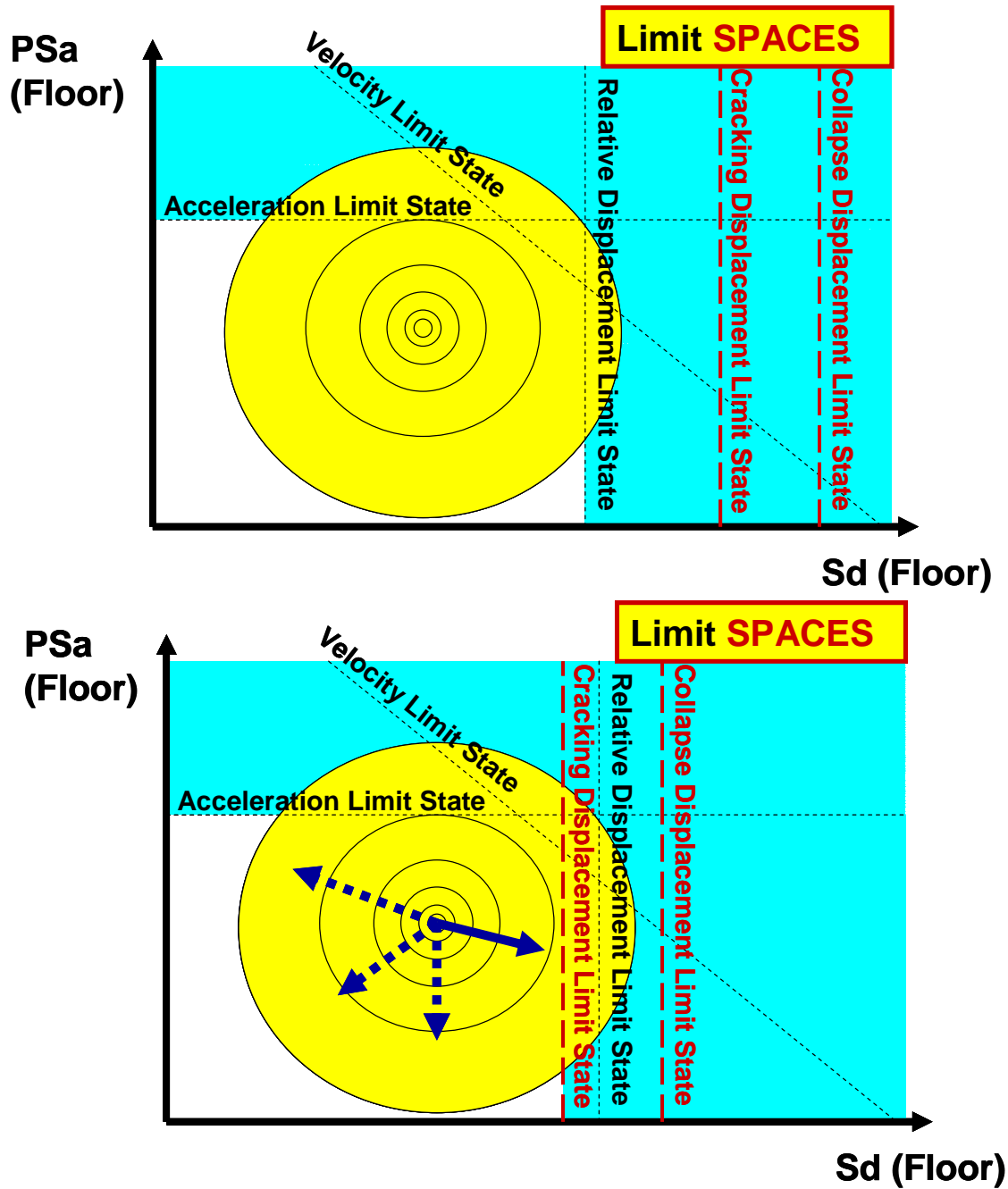
Figure 4. Probability that response exceeds limit space: (a) non-structural limit states reached prior to structural limit states; (b) different sequence of limit states

The probable non-structural loss would be calculated similarly, with the only difference that if the same earthquake was to re-occur at time $t_o^+$, the probability of exceeding the non-structural limit space could increase or decrease, depending on the type of non-structural components, and the extent of structural damage (e.g., a "softer" damaged structure might undergo lower floor accelerations but greater floor inter-story drifts).  For the purpose of Figure 5c and Figure 5d, the assumption of greater probability of non-structural damage is made.
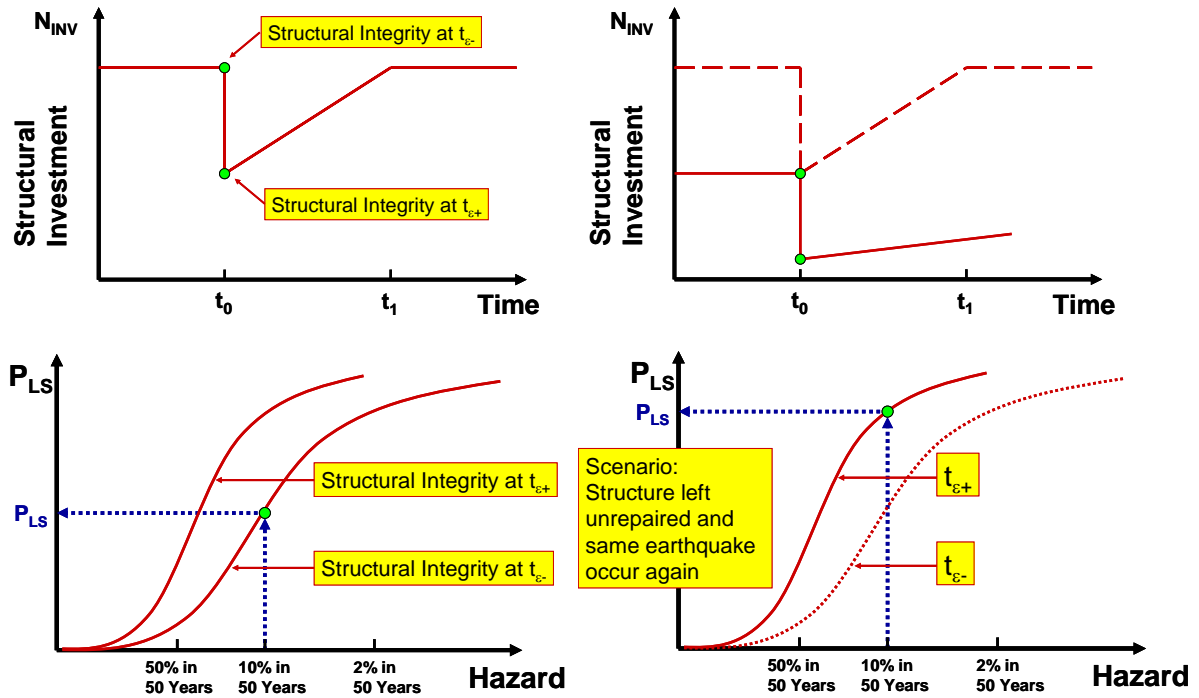
Figure 5. Case of non-linear structural seismic response: (a) Structural resilience curve and corresponding loss in structural integrity as obtained from; (b) Probability of structural loss before earthquake; (c) New structural resilience curve if structure left unrepaired, based on; (d) probability of failure upon repeat of earthquake

Figure 6a and Figure 6b 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 $t_o$ (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 Figure 6c and Figure 6d, that repairs to non-structural components may also be required, and that it is possible to increase the value of the investments (on the basis of the same non-structural components and equipments here, not by adding more of them) to above the pre-earthquake condition, enhancing seismic resilience by reducing the probability of losses in a future repeat of the same earthquake.
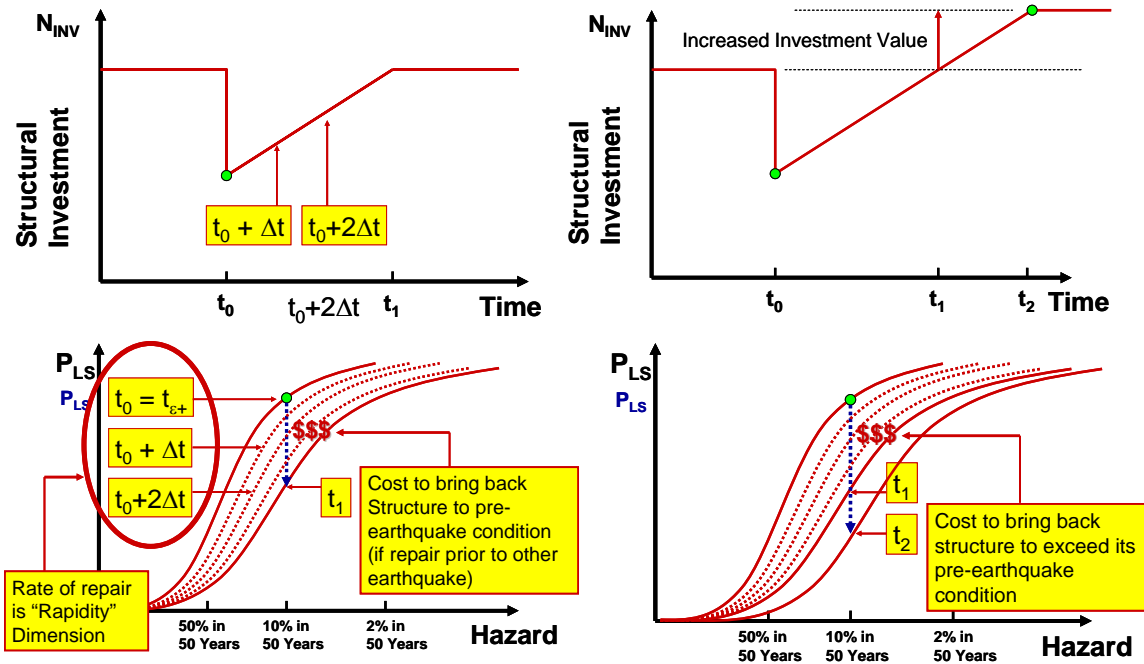
Figure 6. Case of non-linear structural seismic response: (a) Improvement in structural resilience as structure is repaired over time, and; (b) corresponding reduction in probability of structural losses; (c) Increased resiliency to above pre-earthquake condition and; (c) corresponding improvement in probability of structural losses

## 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 non-structural resilience has been illustrated. 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. It also shows how the recognized components of resilience, such as fragility, performance limit states, and response can be effectively influences by response modification or capacity enhancements.

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