



EXPLORING THE CONCEPT OF SEISMIC RESILIENCE FOR ACUTE CARE FACILITIES

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SUMMARY

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 approached such that the engineering sub-problem is formulated, recognizing that, to operate, hospitals intricately depend on the performance of their physical infrastructure (from the integrity of structural systems and non-structural systems, lifelines, components and equipments). Quantification 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 response is considered, as well as impact of retrofit or repair, and impact on time to recovery. 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.

1. 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 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:

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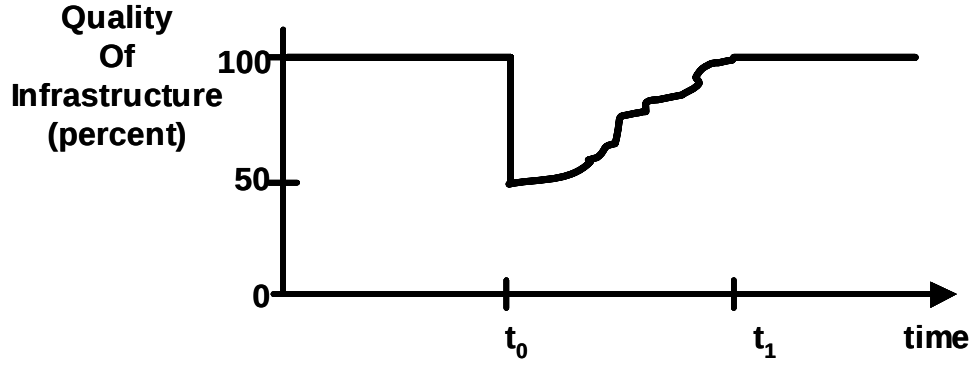


Figure 1: Schematic representation of seismic resilience concept (Bruneau et al. 2003)

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

Much research is needed to quantify resilience, particularly for some type 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 sub-problem that can be addressed and quantified through a coordinated large-scale multidisciplinary earthquake engineering research effort. 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. 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 such, the reader could substitute “earthquake engineering” by “extreme event engineering” throughout without loss of generality. For simplicity here, focus remains on seismic resilience.

2. 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 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. Where resources are scarce, time to recovery lengthens, approaching infinity in 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.

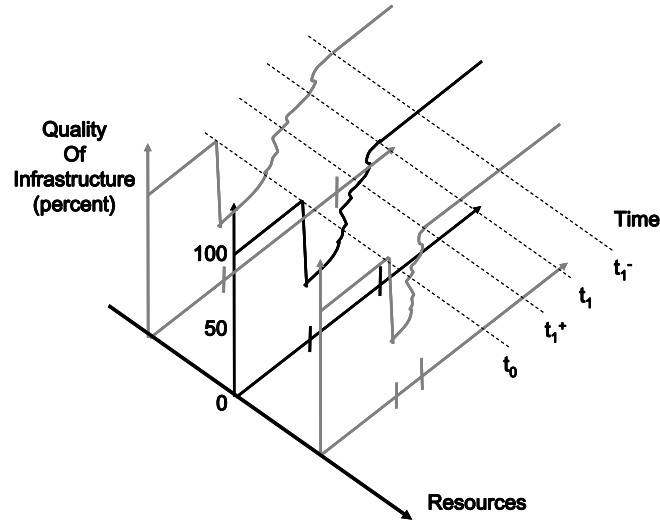


Figure 2: 3-D resilience concept (expanded in resourcefulness dimension)

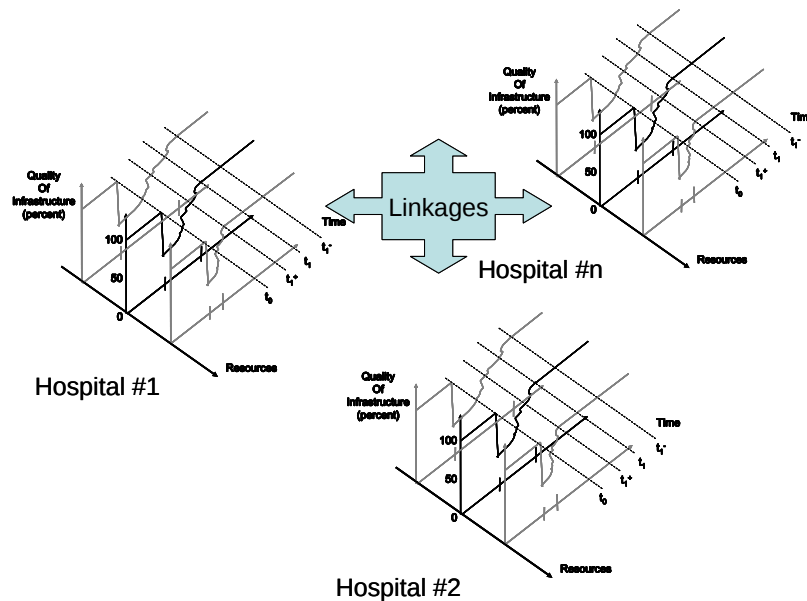


Figure 3: 4-D resilience concept (expanded with redundancy dimension)

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.

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

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

where L (or more specifically $L(t_{0E})$) is the magnitude of loss function, where F (or more specifically $f_{\text{rec}}(t, t_{0E}, T_{RE})$) 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 where 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, $L_{LS}(t_{0E})$ (monetary, physical, technological, and informational) at an expected performance limit state (LS) in respect to the cost of maintaining the full performance measure (FP) expressed in the same units as the loss, expressed as:

$$L(t_{0E}) = \sum_j [L_{LS,j}(t_{0E}) / FP] \cdot P_{LS,j}(R_j \geq LS_j) \quad (3)$$

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; 2000b). 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.

3. RESILIENCE OF ACUTE CARE FACILITIES

Residents in seismic areas have expressed their strong expectation that acute care facilities should 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.

One such option focuses 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 4). 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 allow to illustrate some short term and long term issues whose true impact have often been misinterpreted or exaggerated. For example, prior to an earthquake, the impact of SB1953 is shown (Figure 4) as resulting in the loss of some patients/day capacity, as some hospitals are expected to close rather than invest to meet 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 (Committee 1997) to treat earthquake-related injuries when transportation to a remote facility is difficult, or impossible. This emergency setting usually last but a few days or weeks, and is not a viable solution for an earthquake that would occur in a less accommodating weather or urban setting (such as in New York City, in January). In Figure 4, for convenience, two distinct and concurrent recovery activities has been illustrated as sequential, namely: repair of capacity and rebuilding of capacity, the first dealing with replacement of capacity lost during the earthquake $\alpha_R=1$ in Equation (20), the second related to increasing capacity to the level needed to service the needs of the population ($\alpha_R>1$ in Equation (2)).

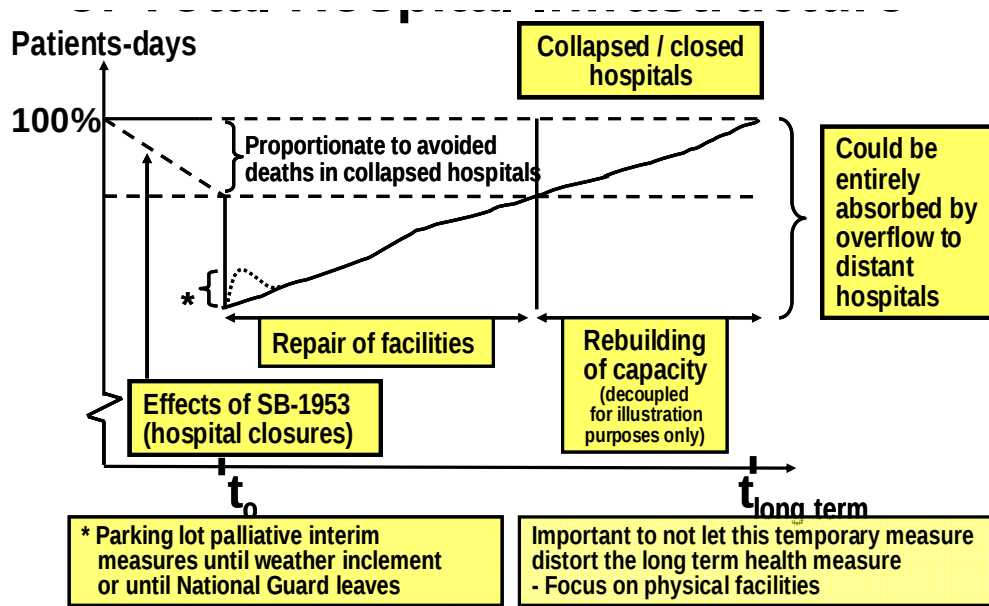


Figure 4: Quantification of seismic resilience of acute care facilities as patients/day treatment capacity of the total available hospital infrastructure

The advantage of this 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 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 requires 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 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 reduce 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 build upon a strong engineering basis (among many things), this quantification must encompass all equipments and units in a given hospital, as well as capture their inter-dependencies; whether some equipments would require replacement or repair following an earthquake is apriori difficult to quantify in engineering terms. Modeling of linkages between geographically distributed hospitals adds another layer of complexity, and for 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 on the fragilities of that network.

4. 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 3-D bell-curve viewed from above can be expressed by isoprobability contours for this purpose – spherical contours here for expediency (Figure 5). Floor pseudo-accelerations (PSA floor) and inter-story drifts (Sd 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 5, 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 5) 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 Sd-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 5). 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 5, 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 5), 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.

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

$$P_{LS} = \lim_{N_{TE} \rightarrow \infty} \left\{ \frac{N_R \left[\left(\frac{R_a}{a_{LIM}} \right)^{N_a} + \left(\frac{R_d}{d_{LIM}} \right)^{N_d} \right]}{N_{TE}} \right\} \quad (4)$$

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; d_{LIM} is the displacement limit threshold. This formulation is an extension of Hwang et al. (2000). Actual response function and limit states are shown in Figure 6.

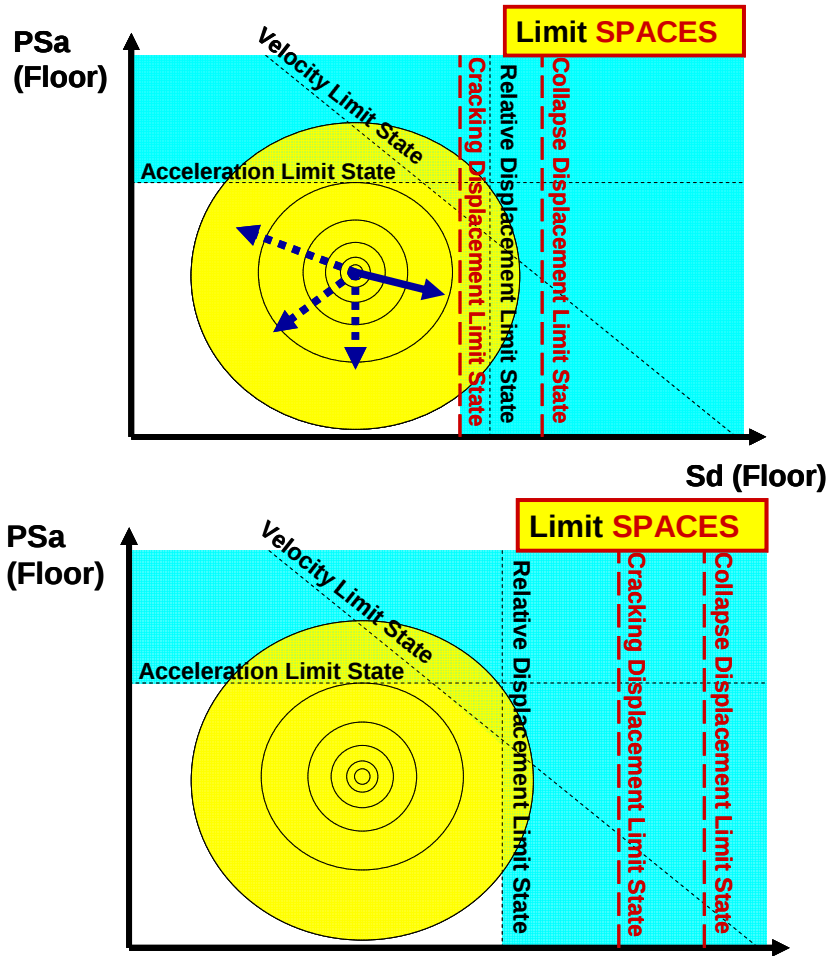


Figure 5: Probability that response exceeds limit space: (a) non-structural limit states reached prior to structural limit states; (b) different sequence of limit states

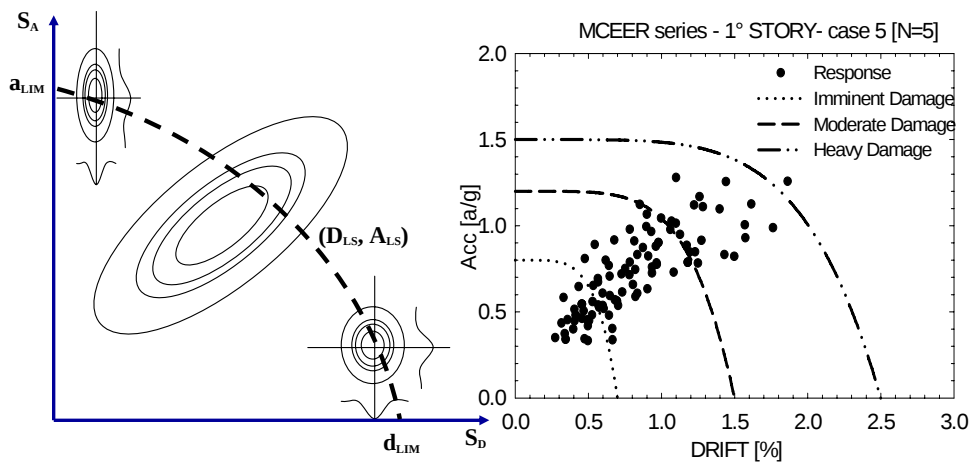


Figure 6: Response function and limit states in actual building: response and limit state distributions (left) and actual data (right)

5. NON-LINEAR INELASTIC STRUCTURAL RESPONSE

Quantification of the seismic resilience curve is presented for the general case of non-linear inelastic 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 non-structural system. The left part of Figure 8 illustrates that there is a structural loss (i.e., drop in the value of structural investment) due to structural damage measurable from the SOMBRERO concept as a function of the quantifiable intersect between the probabilistic response surface and the structural limit states in Figure 7. Such intersect also exists in the OLE for the non-structural components. In both cases, the magnitude of this intersect (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 7c 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 2500 years). The probable non-structural loss, LNSL, can be expressed by the product of the probability of exceeding the performance limit state, PLS, and of the value of replacing the damaged non-structural component versus its initial investment, FP as indicated by Equation (3). For elastic structural response, focus would be on non-structural investment, FP is expressed as NSINV. For the probable exceedance of the limit space shown in Figure 7c for a design level corresponding to a 500-year return period, Figure 7b shows the resulting non-structural resilience curve, with the probable non-structural losses at time t_0 . The time at full recovery to pre-earthquake conditions, t_1 , is entirely related to repair of non-structural damage.

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 7b expresses the resulting probability of exceeding the limit space, PLS, as a function of the earthquake hazard, and Figure 7a the corresponding probable loss in the structural investment, LLS. In this case, which focuses on the structural investment, FP is taken as NINV. As indicated earlier, as a result of damage, the probabilistic response surface has displaced within the OLE of Figure 5 to a new position the instant after time t_0 (labeled t_0^+). If another earthquake was to occur at time t_0^+ , the probability of exceeding the limit state would be significantly greater (as shown in Figure 7b), and a further loss in the structural investment (possibly to collapse) would occur. Note that for inelastic structural response, if the same earthquake was to re-occur at time t_0^+ , 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 7c and Figure 7d, the assumption of greater probability of non-structural damage is made.

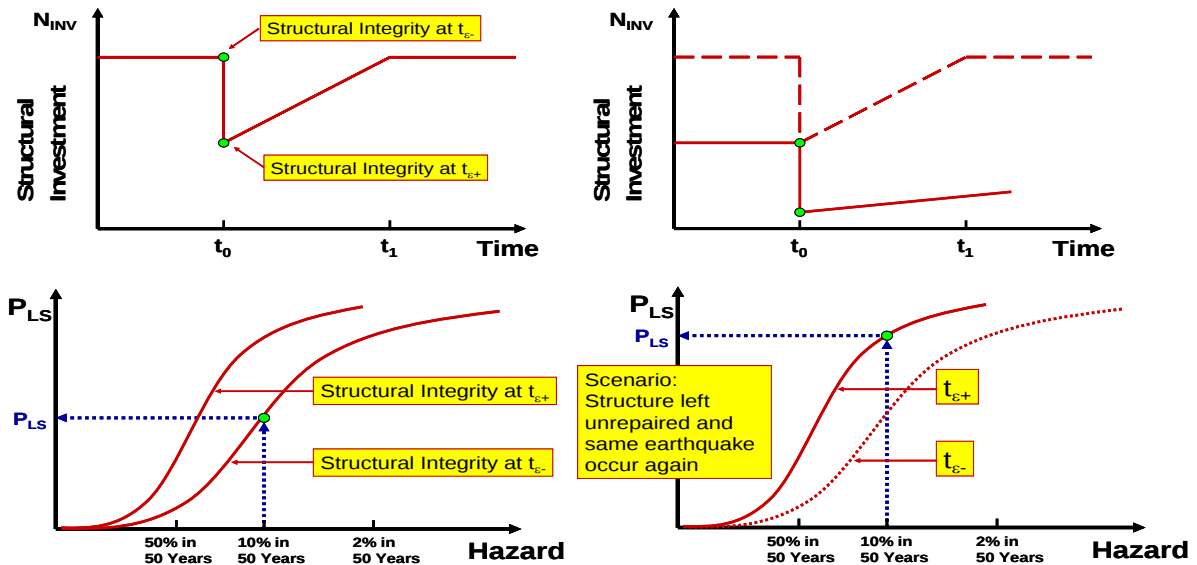


Figure 7: Case of non-linear structural seismic response: (a) Structural resilience curve and corresponding loss in structural integrity as obtained from; (b) Probability of structural loss before earthquake; (c) New structural resilience curve if structure left unrepaired, based on; (d) probability of failure upon repeat of earthquake

Figure 8a and Figure 8b 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 to (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 8c and Figure 8d, 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.

The benefit of retrofitting prior to an earthquake can also be assessed and quantified using the resiliency concept, although this is not presented here due to space constraints.

6. 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 for systems having either linear elastic or non-linear 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. 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.

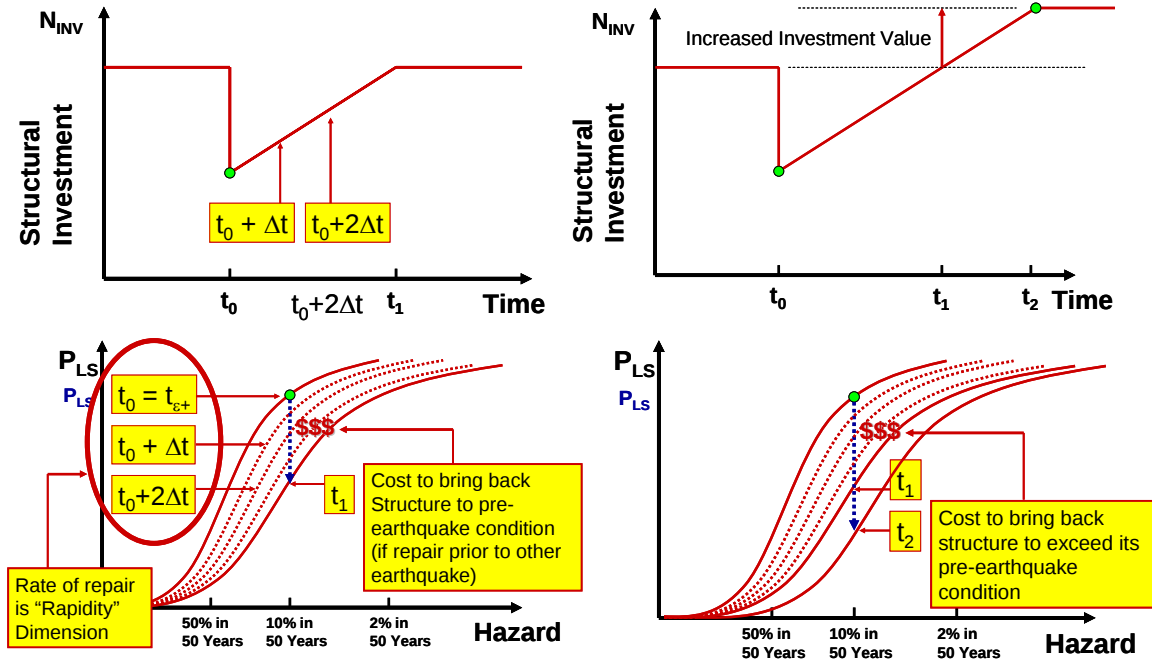


Figure 8: Case of non-linear structural seismic response: (a) Improvement in structural resilience as structure is repaired over time, and; (b) corresponding reduction in probability of structural losses; (c) Increased resiliency to above pre-earthquake condition and; (d) corresponding improvement in probability of structural losses

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