SEISMIC RESILIENCE OF COMMUNITIES – CONCEPTUALIZATION AND OPERATIONALIZATION

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ABSTRACT

A conceptual framework which defines the seismic resilience of communities and quantitative measures of resilience in a manner that can be useful for a coordinated research effort focusing on enhancing this resilience is one of the main themes at the Multidisciplinary Center for Earthquake Engineering Research (MCEER). This framework relies on the complementary measures of resilience: "Reduced failure probabilities", "Reduced consequences from failures", and "Reduced time to recovery". The framework also includes quantitative measures of the "ends" of robustness and rapidity, and the "means" of resourcefulness and redundancy. The ultimate objective of this work is to make the concepts that are presented here adaptable for the analysis of various critical infrastructure elements (both as individual systems and as interrelated sets of systems) exposed to both natural and man made disasters.

Keywords: Performance, resilience, recovery, redundancy, socio-economic

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 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 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

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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 occurs at time t_0, it could cause sufficient damage to the infrastructure such that the quality 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 (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:

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

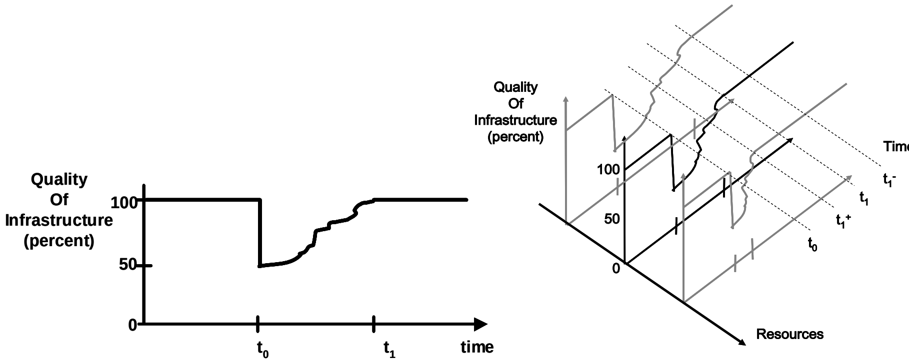

Figure 1. Resilience functions: basic (left), multi-dimensional (right)

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 use for the formulation of strategies and policies at a higher level.

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 units 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 units 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 unit of analysis.
- Rapidity: the capacity to meet priorities and achieve goals in a timely manner.

As such the vertical and horizontal axes in Figure 1 (left) 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 as is illustrated in Figures 1 (right) by a third axis, that added resources can be used to reduce time to recovery. 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.

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 (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.

To quantify the seismic resilience, the quantity to be measured by the vertical axis of the resilience chart must first be defined.

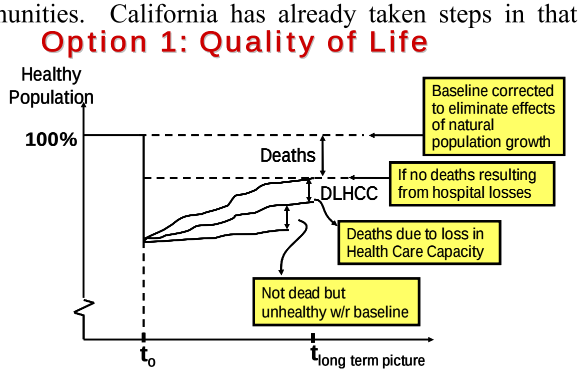

Figure 2- Quality of life – measure of performance.

A first option is to quantify quality of life as the percentage of healthy population (Figure 2). Using the total healthy population in 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 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. Injuries suffered during the earthquake would account for the remaining reduction in the healthy population at time t_0. In the best of scenario, in 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 that could have been prevented if the health care system capability had not been reduced by the earthquake. This approach has the advantage that it seeks to quantify the impact of an earthquake on the health of a population, a significant measure for the purpose of policy making.

A second, alternative, option focuses on relating the seismic resilience of facilities to the number of patients/day that can be provided as a measure of the treatment capacity of the health care facilities (Figure 3). For example, prior to an earthquake, the impact of SB1953 is shown (Figure 3) as resulting in the loss of some patients/day capacity, as some hospitals are expected to close. Following the major loss of patients/day capacity directly attributed to the earthquake, is the short burst of recovered patients /day capacity as a consequence of the "parking-lot" medicine provided outside of hospital facilities. In Figure 3, for convenience, two distinct and concurrent recovery activities are illustrated as sequential, namely: repair of capacity and rebuilding of capacity.

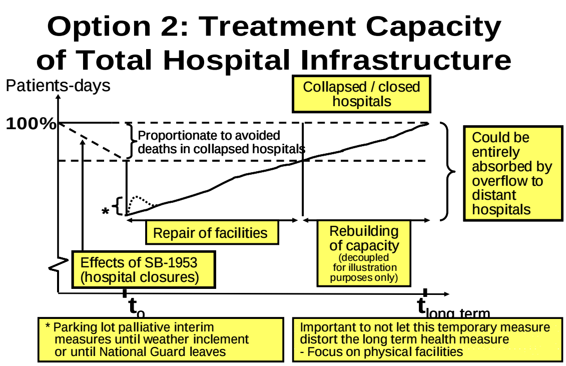

Figure. 3 – Hospital capacity –measure of performance

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. 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 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. In this respect, these engineering quantification tools could be used to assess whether the seismic resilience is enhanced or not, i.e. whether a set of interventions reduce the loss in patient-day capacity, or if a local overflow can be absorbed globally, and how long will take to restore capacity.

4. RESILIENCE OF STRUCTURAL AND NON-STRUCTURAL 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 non-structural components.

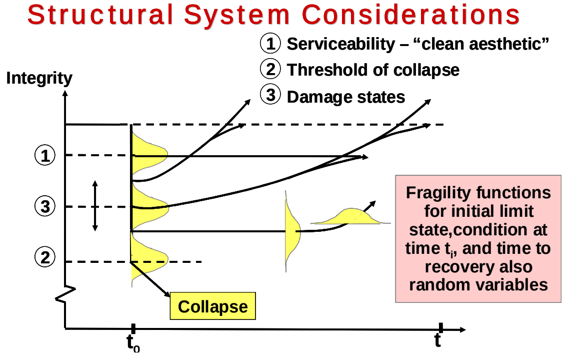

Figure 4: Probabilistic aspect of seismic resilience, (structural integrity example)

In light of the considerable uncertainties inherent to the field of earthquake engineering (both in the demands estimated through engineering seismology, and in the capacities that ensue from the non-linear inelastic seismic performance of the structure), the quantification of seismic resilience proceeds through a probabilistic frame-work, as illustrated in Figure 4. A serviceability level is defined as a small loss in structural integrity. A collapse level is defined as the maximum loss of integrity prior to 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. It is also illustrated that over time, structural integrity could return to the initial pre-earthquake condition, to less than this condition (e.g. cracking in some structural element may never be repaired), or above this condition if the structure is repaired to a superior seismic performance level. The bell-curves show that these integrity levels are random variable.

One way to achieve quantification of engineering seismic resilience is through the concept of Multidimensional Bell-curve of Response. Therefore, for the purpose of this discussion, the probability distribution surface schematically shown in Figure 5 is used. Viewed from above, the surface can be expressed by isoprobability contours. Spherical contours are used here for expediency. Floor pseudo-accelerations (PSA floor) and interstory drifts (S_d floor) express the Limit Space (LS), with specific structural and non-structural limit states shown by dotted lines; for the former, a serviceability limit state (cracking of concrete structural elements) and a collapse limit state are indicated. Deterministic limit states are used here, but need not be. Floor acceleration and interstory drift are therefore the structural response probabilistic parameters considered here by the bell distribution. 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, 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 exceedence of the limit state. However, modifications to the structural system change the probable structural response, which is equivalent to sliding the multidimensional bell-curve within the limit space (i.e. moving along the dotted arrows in Figure 5). For example, stiffening the structural system in a manner that reduce interstory drifts would move the response surface to the left of the limit space 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, 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.

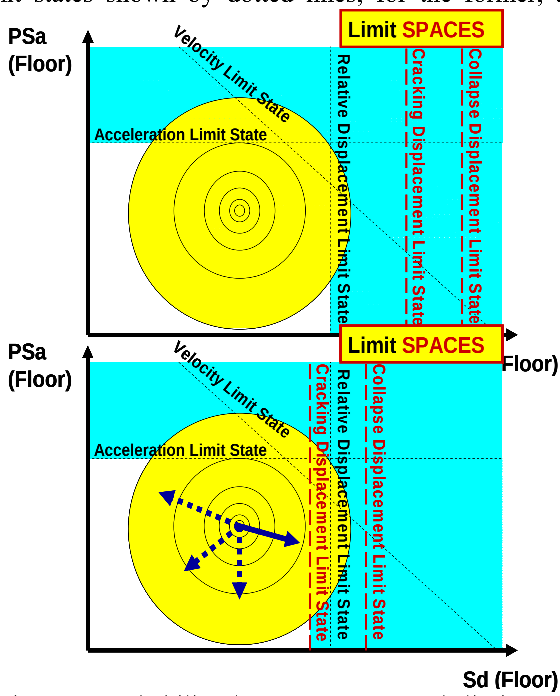

Figure 5: Probability that response exceeds limit space: (a) non-structural limit states vs structural limit states; (b) different sequence of limit states

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 non-structural system. The left part of Figure 6 illustrates that there is no structural loss (i.e. no drop in the value of structural investment) when the structure remains elastic. This is equivalent to having no significant intersect between the probabilistic response surface and the structural limit states in Figure 5a. However, such intersect exists in the limit space for the non-structural components, and 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 6c expresses the resulting probability of exceeding the limit space as a function of the earthquake hazard (itself expressed in probability of exceedence over 50 years, in a manner compatible with code documents – 50%, 10% (500 years return period), and 2% probability of exceedence.. The probable non-structural loss, P_{NSL}, can be expressed by the product of the probability of exceeding the limit state, P_{LS}, and of the value of the non-structural investment, NS_{INV}. For the probable exceedence of the limit space shown in Figure 6c for a design level corresponding to a 500-year return period, Figure 6b 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.

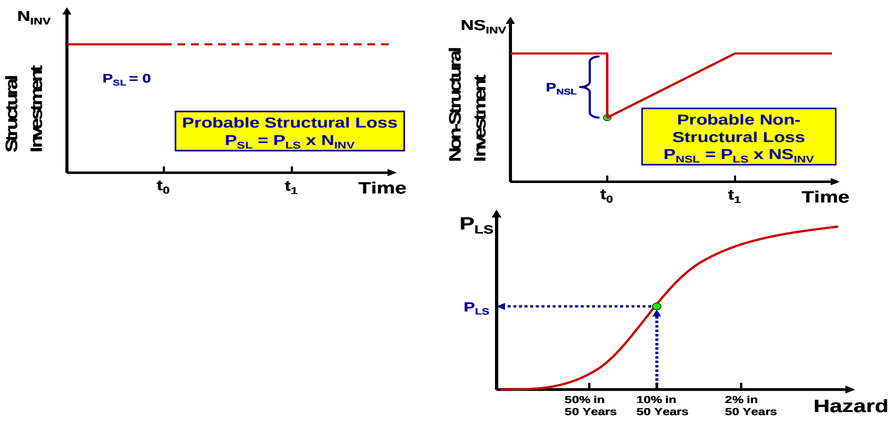

Figure 6: Probable non-structural loss in case of linear-elastic structural response

Quantification of the seismic resilience curve for the case of non-linear inelastic structural response differ 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 fragility concept since there is now a quantifiable intersect between the probabilistic response surface and the structural limit states in Figure 5b. Figure 7b expresses the resulting probability of exceeding the limit space, P_{LS}, as a function of the earthquake hazard, and Figure 7a the corresponding probable loss in the structural investment, P_{LS}. 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.

The probable non-structural loss would be calculated as before, 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 interstory drifts). For the purpose of Figures 7c and 7d, the assumption of greater probability of non-structural damage is made.

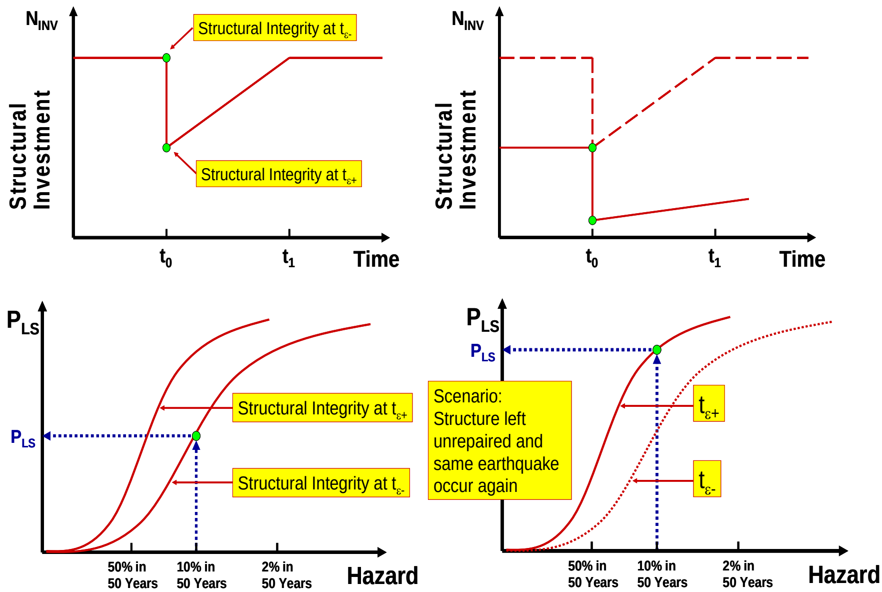

Figure 7: Case of structural seismic response: (a) Structural resilience curve and corresponding loss in structural integrity as obtained from; (b) Probability of structural loss before earthquake; (c) New structural resilience curve if structure left unrepaired, based on; (d) probability of failure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

Structural repairs 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, 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 presented in Figures 8. To illustrate how this is achieved, the fragility curves at times t_o^- and t_o^+

of Figure 7a will be used. It is assumed 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 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 here as the "Reinhorn-Bruneau Sliding Pair of Fragility Curves" assumption. As shown in Figure 8, once the structure has been retrofitted, the investment in the structural system has been increased, which translates into the elevated resilience curve of Figure 8b. Furthermore, should the same expected earthquake occurs (with a return period corresponding to 10% change of exceedence in 50 years for the example in Figure 8a), 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 8b.

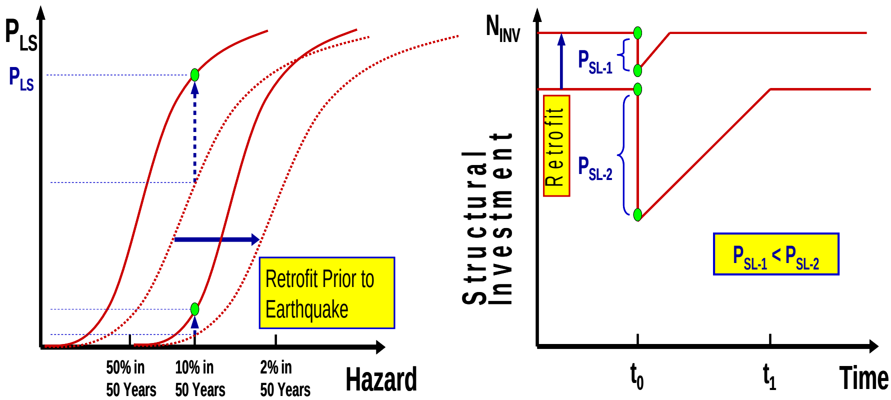

Figure 8: Non-linear structural seismic response: (a) Bruneau/Reinhorn assumption of sliding proportional fragility curve sets; (b) Enhancement of resilience curve to reduced probability of losses due to seismic retrofit prior to earthquake

The corresponding impact of either structural damage or seismic retrofit on the fragility and resilience curves of non-structural component for the case of non-linear structural seismic response and non-retrofitted non-structural 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 non-structural component would depend on the response distribution (the Demand) and the limit space (the Capacity).

To establish the relationships between various engineering measures and loss of patients/day capability requires integrating (quantitatively) component fragilities (including non-structural, structural, geotechnical, etc.) into a system resilience (using the same units as presented in this paper).

5. CLOSING REMARKS

A possible final quantification of seismic resiliency assessment could be stated in a format 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).

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. This points to the need for a quantitative probabilistic framework and tools anchored in engineering procedures to guide decision makers in consideration of policies, rather than to focus on 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. 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 re-assess their perceptions.

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