13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2575

A FRAMEWORK TO QUANTITATIVELY ASSESS AND ENHANCE THE SEISMIC RESILIENCE OF COMMUNITIES

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SUMMARY

This paper presents a conceptual framework to define seismic resilience of communities and quantitative measures of resilience that can be useful for a coordinated research effort focusing on enhancing this resilience. 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, and integrates those measures into the four dimensions of community resilience — technical, organizational, social and economic.

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INTRODUCTION

Agencies and other groups engaged in disaster mitigation have placed much emphasis in recent years on the objective of achieving disaster-resilient communities. For example, by establishing Project Impact in 1997, the Federal Emergency Management Agency initiated a series of community-based pre-disaster mitigation programs designed to foster public-private partnerships that would undertake hazard and risk assessments, community education programs, and mitigation projects to reduce future earthquake losses (FEMA [1], Nigg [2]). Although Project Impact is no longer receiving federal funding, programs remain active in more than two hundred communities around the United States. The Disaster Mitigation Act of 2000, which requires communities to engage in mitigation and preparedness planning and offers other incentives for disaster mitigation, also signals a move toward higher levels of community disaster resistance. Scholarship in the hazards field has also increasingly emphasized strategies that are needed to make communities disaster resistant while addressing long-term issues of sustainability and quality of life (Mileti [3]).

Because of their potential for producing high losses and extensive community disruption, earthquakes have been given high priority in efforts to enhance community disaster resistance. The implementation of voluntary practices or mandatory policies aimed at reducing the consequences of an earthquake, along with training and preparedness measures to optimize the efficiency of emergency response immediately after a seismic event, all contribute to abating the seismic risk and the potential for future losses. While these activities are important, justified, and clearly related to resilience enhancement, there is no explicit set of procedures in the existing literature that suggest how to quantify resilience in the context of earthquake hazards, how to compare communities with one another in terms of their resilience, or how to determine whether individual communities are moving in the direction of becoming more resilient in the face of earthquake hazards. Considerable research has been accomplished to assess direct and indirect losses attributable to earthquakes, and to estimate the reduction of these losses as a result of specific actions, policies, or scenarios. However, the notion of seismic resilience suggests a much broader framework than the reduction of monetary losses alone. Equally important, in addition to focusing on the losses earthquakes produce, research must also address the ways in which specific pre- and post-event measures, and strategies can prevent and contain losses.

All earthquake engineering research can contribute to improve the state of the art, thus eventually leading to superior knowledge on how to reduce the seismic risk. Hence, a key objective of all research undertaken with respect to seismic hazards is to develop new knowledge or technologies to enhance seismic resilience. However, there is a need to move beyond qualitative conceptualizations of disaster resistance and resilience to more quantitative measures, both to better understand factors contributing to resilience and to assess more systematically the potential contributions and benefits of various research activities. It is therefore necessary to clearly define resilience, identify its dimensions, and find ways of measuring and quantifying those dimensions. With this end in mind, the authors have developed both a conceptual framework and a set of measures that make it possible to empirically determine the extent to which different units of analysis and systems are resilient. This paper outlines that framework, discusses ways of quantifying system performance criteria, and uses a systems diagram to illustrate how resilience can be improved through system assessment and modification in both pre-earthquake and post-earthquake contexts. The goal of the paper is to stimulate discussion within the earthquake research community about concepts, indicators, and measures that are linked to resilience and about alternative strategies for achieving resilience both in engineered and community systems.

GENERAL MEASURES OF RESILIENCE

Defining Resilience

The concept of resilience is routinely used in research in disciplines ranging from environmental research to materials science and engineering, psychology, sociology, and economics. The notion of resilience is commonly used to denote both strength and flexibility. One dictionary definition defines resilience as "the ability to recover quickly from illness, change, or misfortune. Buoyancy. The property of a material that enables it to assume its original shape or position after being bent, stretched, or compressed. Elasticity." (Webster's Comprehensive Dictionary [4]). Resilience has been defined as "the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back" (Wildavsky [5]) and as "the ability of a system to withstand stresses of 'environmental loading'…a fundamental quality found in individuals, groups, organizations, and systems as a whole (Horne [6]). Focusing on earthquake disasters and specifically on post-disaster response, (Comfort [7]) defines resilience as "the capacity to adapt existing resources and skills to new situations and operating conditions." The term implies both the ability to adjust to "normal" or anticipated levels of stress and to adapt to sudden shocks and extraordinary demands. In the context of hazards, the concept can be thought of as spanning both pre-event measures that seek to prevent hazard-related damage and losses and post-event strategies designed to cope with and minimize disaster impacts.

For purposes of this discussion, community seismic resilience is defined as the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes. The objectives of enhancing seismic resilience are to minimize loss of life, injuries, and other economic losses, in short, to minimize any reduction in quality of life due to earthquakes. Seismic resilience can be achieved by enhancing the ability of a community's infrastructure (e.g., lifelines, structures) to perform during and after an earthquake, as well as through emergency response and strategies that effectively cope with and contain losses and recovery strategies that enable communities to return to levels of predisaster functioning (or other acceptable levels) as rapidly as possible.

Numerous institutions, organizations, and elements in the built environment contribute to community resilience. However, as a starting point, it is logical to begin analyzing resilience by focusing on organizations whose functions are essential for community well-being in the aftermath of earthquake disasters. These critical facilities include water and power lifelines, acute-care hospitals, and organizations that have the responsibility for emergency management at the local community level.

Improving the resilience of critical lifelines such as water and power and critical facilities and functions such as emergency response management is critical for overall community resilience. These organizations form the "backbone" for community functioning; they enable communities to respond, provide for the well-being of their residents, and initiate recovery activities when earthquakes strike. For example, since no community can cope adequately with an earthquake disaster without being able to provide emergency care for injured victims, hospital functionality is crucial for community resilience. Water is another essential lifeline service that must be provided to sustain disaster victims. Any consideration of resilience must begin with a focus on services and functional activities that constitute the backbone of a resilient community. The continued operation and rapid restoration of these services are a necessary condition for overall community resilience.

Quantifying the Concept of Resilience

At any given time, the actual or potential performance of any system can be measured as a point in a multidimensional space of performance measures. Over time, performance can change, sometimes gradually, sometimes abruptly. Abrupt changes in performance occur in the case of disastrous events like a major earthquake. In these cases, a system can fail, leading to a major reduction or complete loss in performance with respect to some or all measures. Resources are then needed to restore a system's performance to its normal levels. Similarly, the performance of a system over time can be characterized as a path through the multidimensional space of performance measures. Normal fluctuations will show as minor fluctuations in performance. Disastrous events create abrupt changes in performance, followed by a gradual restoration to normal performance levels, depending on the resources employed.

This characterization of system performance leads to a broader conceptualization of resilience. Resilience can be understood as the ability of the 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). 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.

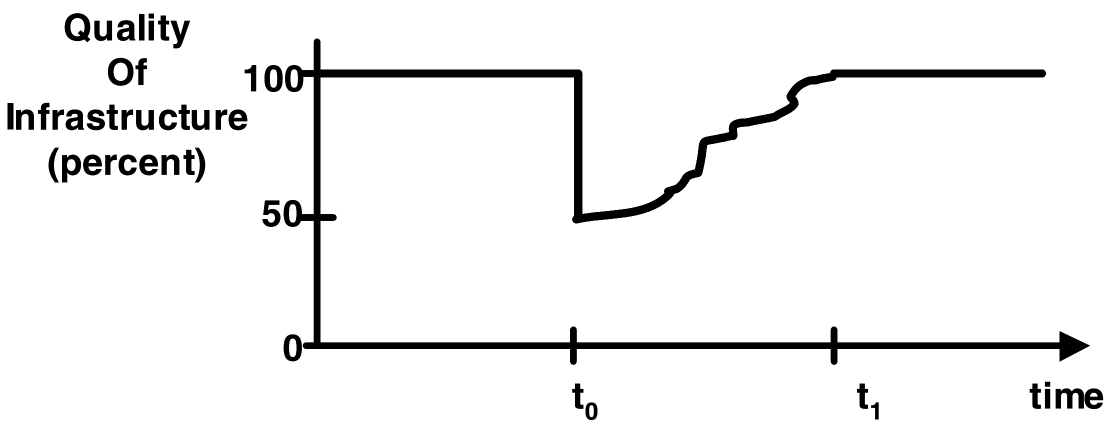

Figure 1. Measure of seismic resilience — conceptual definition.

This approach is based on the notion that a measure, Q(t), which varies with time, has been defined for the quality of the infrastructure of a community. Specifically, performance can range from 0% to 100%, where 100% means no degradation in service and 0% means no service is available. 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:

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

Obviously, community seismic resilience must be measured in light of the full set of earthquakes that threaten a community, and therefore must include probabilities of the occurrences of various earthquakes. Furthermore, return to 100% pre-event levels may not be sufficient in many instances, particularly in communities where the existing seismic resiliency is low, and post-event recovery to more than 100% pre-earthquake levels are often desirable. These complexities, and others, can be taken into account in specific research activities. Yet, even in its simplest form, applying this general concept to the various specific physical and organizational systems that can be impacted by earthquakes presents significant conceptual and measurement challenges.

DIMENSIONS OF RESILIENCE

As discussed above, seismic resilience is conceptualized as the ability of both physical and social systems to withstand earthquake-generated forces and demands and to cope with earthquake impacts through situation assessment, rapid response, and effective recovery strategies (measured in terms of reduced failure probabilities, reduced consequences, reduced time to recovery). 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. Resourcefulness can be further conceptualized as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources 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 and avoid future disruption

However, resilience can also be conceptualized as encompassing four interrelated dimensions: technical, organizational, social, and economic. The *technical* dimension of resilience refers to the ability of physical systems (including components, their interconnections and interactions, and entire systems) to perform to acceptable/desired levels when subject to earthquake forces. The *organizational* dimension of resilience refers to the capacity of organizations that manage critical facilities and have the responsibility for carrying out critical disaster-related functions to make decisions and take actions that contribute to achieving the properties of resilience outlined above, that is, that help to achieve greater robustness, redundancy, resourcefulness, and rapidity. The *social* dimension of resilience consists of measures specifically designed to lessen the extent to which earthquake-stricken communities and governmental jurisdictions suffer negative consequences due to the loss of critical services as a result of earthquakes. Similarly, the *economic* dimension of resilience refers to the capacity to reduce both direct and indirect economic losses resulting from earthquakes.

These four dimensions of community resilience — technical, organization, social and economic (TOSE) — cannot be adequately measured by any single measure of performance. Instead, different performance measures are required for different systems under analysis. Research is required to address the quantification and measurement of resilience in all its inter-related dimensions — a task that has never been addressed by the earthquake research community.

Figure 2 links the four TOSE dimensions to key community infrastructural elements: power, water, hospital, and local emergency management systems. These systems are to some extent interdependent (e.g., power is needed for water delivery, water is needed by hospitals). As noted earlier, improving the performance of these systems is critical for improving overall community resilience to disasters. For each of these critical systems, *technical* and *organizational* performance measures can be defined that refer to the ability of the physical system and the organization that manages it to withstand earthquake forces and recover quickly from earthquake impacts. The performance of these systems critically affects disaster resilience for the community as a whole.

At the community level, *social* and *economic* performance measures can be defined that refer to the ability of the community to withstand and recover quickly from the disaster. For example, one social measure of community performance involves the community's capacity to provide housing for residents (Comerio [8]). Enhancing construction practices and retrofits make single- and multifamily housing more resistant to earthquakes, but since these dwellings can also become uninhabitable due to lifeline service disruption, enhancing the earthquake resistance of lifeline systems such as water and electrical power also contributes to resilience with respect to the housing supply. Following an earthquake, the rapid provision of emergency shelter and short-term housing for earthquake victims, rapid response on the part of lifeline organizations to restore services to residential dwellings, and government programs and insurance payouts that facilitate housing reconstruction further contribute to community resilience. These measures can be quantified, making it possible to assess communities according to their ability to mitigate housing damage and respond effectively and in a timely manner to disaster-induced housing losses.

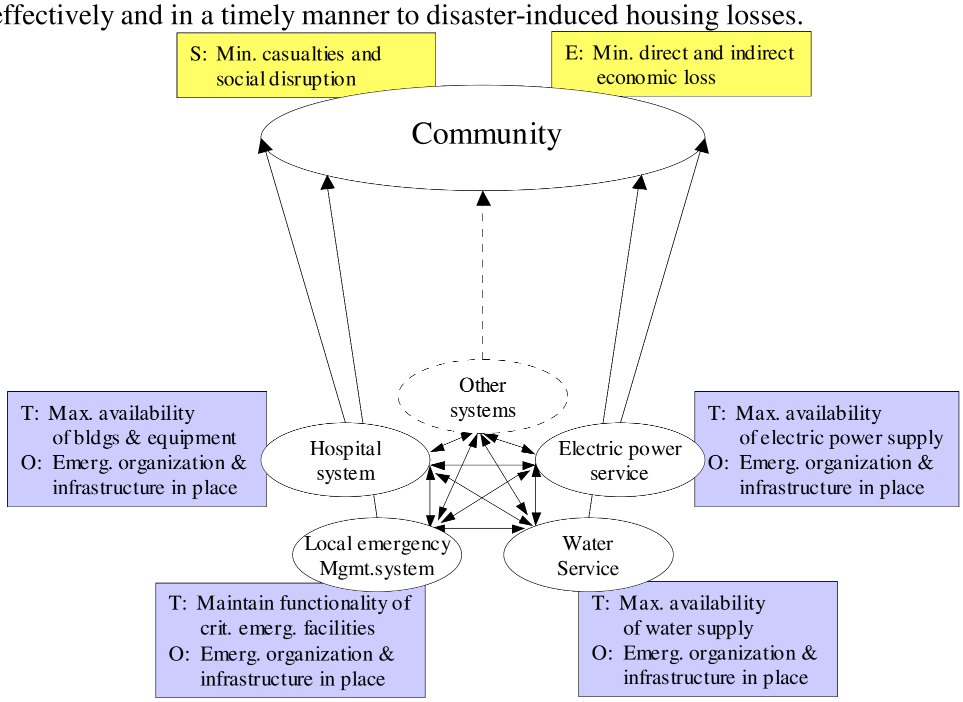

Figure 2. System and community performance measures.

As the examples above show, community resilience can be quantified and measured in various ways. Additional research is required, first to identify and quantify performance measures for resilient systems, and then to assess the extent to which various technologies and tools result in improvements in performance.

QUANTIFICATION OF SYSTEM PERFORMANCE CRITERIA

Measures of Resilience

As indicated earlier, quantifying infrastructure systems and community resilience is a complex process, and scales for measuring resilience — at any level — do not currently exist. Having such scales would be useful in the following ways:

- Identifying ways to improve community resilience
- Identifying and designing research that will ultimately lead to improving community resilience
- Evaluating the relative contribution of different loss-reduction measures to resilience
- Helping to select the measures that achieve desired levels of resilience most reliably and at the least cost.

In principle, the strategy for measuring community resilience is to quantify the difference between the ability of a community's infrastructure to provide community services prior to the occurrence of an earthquake and the expected ability of that infrastructure to perform after an earthquake. Some of the factors that must be addressed in developing an appropriate scale include:

- The quality of the community infrastructure prior to any earthquakes
- The expected reduction in quality of the infrastructure over time due to the occurrence of any earthquake
- The expected length of time that the infrastructure quality is below the pre-earthquake level, and
- The set of all possible earthquakes that threaten a community and their probabilities of occurrence.

Examples of system-wide ("global") measures of performance, as well as measures for various critical systems (power and water lifelines, hospitals, and community response system) are presented in Appendix A. These measures are defined in terms of the 4 R's (robustness, redundancy, resourcefulness, and rapidity) and TOSE dimensions (technical, organizational, societal, and economic). It must be noted that these are for illustrative purposes only. A distinction is also made in the matrices between "ends" and "means" dimensions of resilience. For example, robustness and rapidity are essentially the desired "ends" that are accomplished through resiliency-enhancing measures and are the outcomes that more deeply affect decision makers and stakeholders. Redundancy and resourcefulness are measures that define the "means" by which resilience can be improved. For example, resilience can be enhanced by adding redundant elements to a system. All elements of resilience are important, but robustness and rapidity are seen as being key in measuring system and community resilience, particularly in terms of the resiliency measures expressed by Figure 1.

Conceptually, system performance criteria (defined by technical and organizational measures) are defined in terms of desired community performance outcomes, as reflected by social and economic measures. Therefore, a key research focus initially is to concentrate on refining the social and economic measures of community resilience and translating these measures into system performance criteria (technical and organizational).

Finally, it must be understood that the performance matrices in Appendix A are a work in progress (to illustrate the definitions). Through research, these measures will be re-examined and refined to be more consistent with the notion of system and community resilience, and to further clarify distinctions among some resiliency measures. Furthermore, future work will favor research on those resiliency factors that represent the “end product” of resilience (robustness and rapidity) versus those that help to enhance resilience (redundancy and resourcefulness).

SYSTEMS DIAGRAM

The systems diagram in Figure 3 identifies the key steps required to quantifying infrastructure systems and community resilience. It describes how the performance criteria introduced earlier can be used to determine the extent to which a system is resilient. In addition, the chart shows how new approaches, such as the use of advanced technologies and decision support systems can be incorporated to improve the resilience of an infrastructure system.

This process can be implemented in a series of analytical steps, briefly summarized here. This analytical framework addresses how the multitude of resilience measures illustrated in the tables presented in Appendix A can be integrated into a consistent and defensible method of quantitatively evaluating resilience and resilience improvement, at both the infrastructure system and community levels. The analytical framework focuses on the two desired “ends” of resilience — robustness and rapidity — and assumes that quantitative measures can be developed, as suggested in Appendix A.

For an infrastructure system, technical and organizational resilience can be measured as the annual probability that the system can satisfy the robustness and rapidity criteria with respect to earthquake risk (boxes 6 and 7 in Figure 3). This probability can be evaluated (boxes 5 and 6), for example, by evaluating the performance of an infrastructure system in a series of scenario earthquakes (boxes 1, 4, and 2, possibly replaced by boxes 3, 2, and 4 for an actual earthquake). The expected reduction in performance (reduction in power supply for an electric power system, for example) and expected time to recovery could then be evaluated for each of the earthquake scenarios (boxes 9 and 10). Identifying those scenarios that meet technical and organization resilience criteria, and aggregating the scenario probabilities of occurrence, would yield an estimate of annual probability indicating overall resilience reliability for the electric power system. If expected resilience is deemed to be below the desired targets, options are to focus on response and recovery preparedness (box 11) and/or modify the system to enhance its resilience (box 12). Water, hospital, and emergency response and recovery systems can be treated in a similar fashion with suitably defined performance criteria.

At the community level, social and economic resilience can be evaluated analogously. For example, advanced loss estimation models can be applied to estimate the economic consequences of damage and disruption sustained by the power, water, hospital, and emergency response and recovery systems. The extent to which an earthquake causes a reduction in gross regional product (GRP) can be viewed as an indicator of economic robustness or the lack of it, for example, and the time for GRP to recover to without-earthquake levels is an indicator of the rapidity dimension of economic resilience. As indicated above in the discussion on housing and community resilience, measures of social resilience can be evaluated similarly. The number of scenarios in which the robustness and rapidity criteria are met, and their associated probabilities of occurrence, then indicate the annual probability that resilience criteria are satisfied at the community level.

At both the infrastructure systems and community levels, the annual probability of achieving resilience can be evaluated for cases with and without the application of specific advanced technologies (e.g., new materials, response modification technologies). The difference would directly indicate the potential resilience improvement from applying the advanced technology. While advanced technologies will generally yield improvements in system robustness, some advanced methodologies (e.g., decision-support systems, and/or rapid repairs technologies) could foster resilience by improving restoration rapidity. Other advanced methodologies (e.g., system models and advanced economic models) are needed to quantitatively estimate resilience more accurately, with reduced levels of uncertainty associated with resilience estimates.

Because the systems diagram associates research tasks with the quantification or enhancement of systems and community resilience, it can also be used as a management tool for a coordinated research effort.

Note that Figure 3 is a "free-form" version of a more structured Systems Diagram that more exhaustively portrays the assessment of resilience as a set of "feedforward" and "feedback" loops, and which is presented in Figure 4.

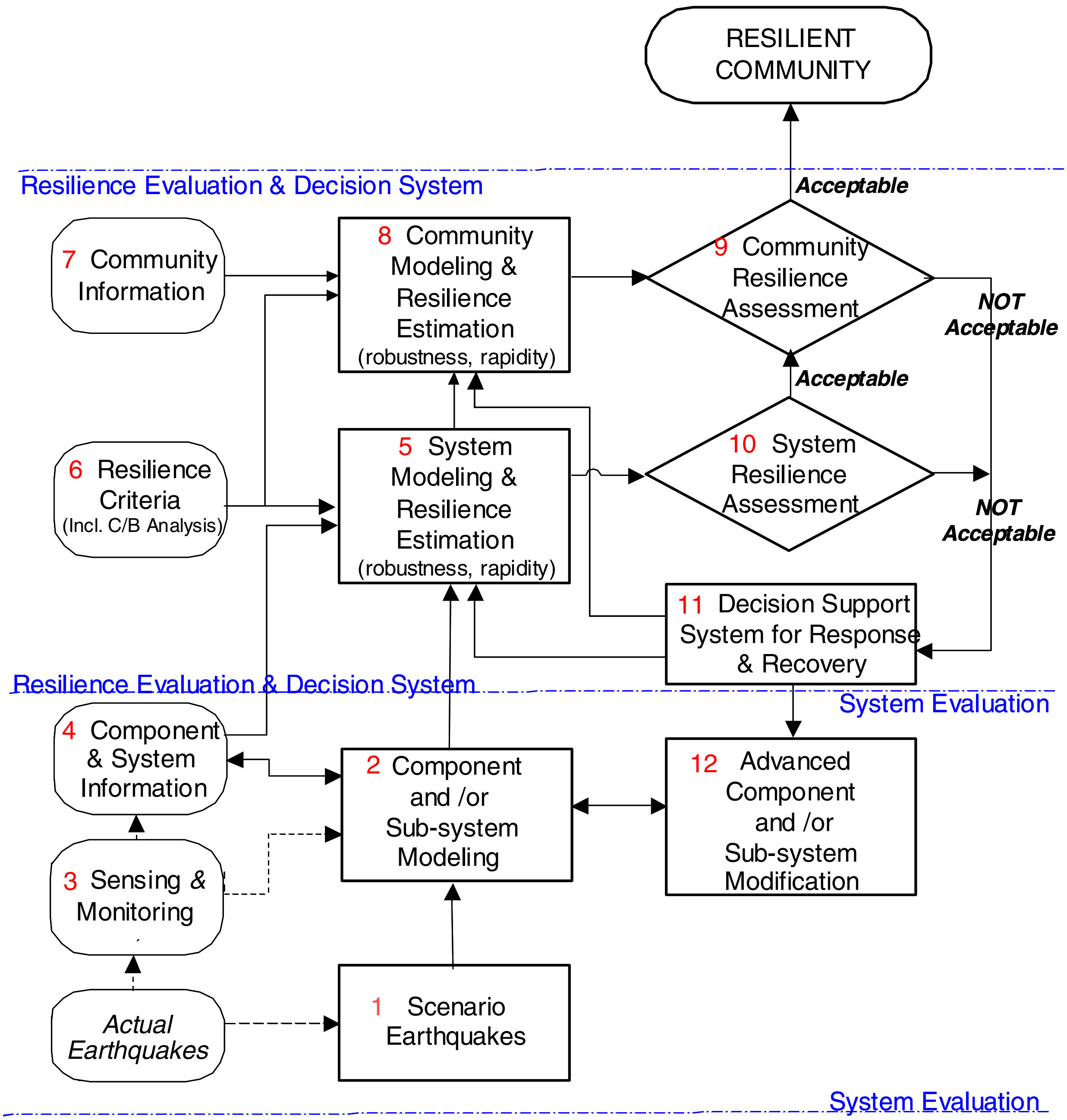

Figure 3. Systems diagram.

The framework presented in Figure 4 is based on concepts that may be more familiar to systems engineers experienced with control algorithms, more specifically the open and closed loop systems theory (also referred to as "feedforward" and "feedback" loops). The open loop system, indicated by the clockwise flow of steps on the left, is applicable to actions that can be taken prior to an earthquake, while the closed loop system, indicated by the counterclockwise flow of actions on the right, is applicable to actions that can be taken following an earthquake. An important distinction to make is that all research and development actions obviously take place prior to an earthquake. However, the feedforward and feedback loops refer to whether the developed technologies focus on pre-event actions (e.g., seismic retrofit), or post-event actions (e.g. response and recovery). However, because the chart is symmetric about a vertical axis, a first level of simplicity could be gained by merging the feedforward and feedback loops into one, to avoid possible syntax and philosophical arguments on what constitutes a pre-event or post-event activity. The systems diagram included in Figure 3 has implemented this simplification, by presenting a single loop without distinction made between pre-event and post-event matters. However, the control loops approach, at the cost of more complexity, can be a powerful planning tool for the development of coordinated efforts.

The systems diagram presented in Figure 4 is also structured in three horizontal layers. The bottom layer is representative of the situation where no intervention is made on the existing systems; earthquakes occur, impact the systems (e.g., infrastructure), and disasters ensue. The second layer addresses a first level of actions and decisions in which decisions are made based on simple triggers; for example, a code-specified drift limit triggers some actions if exceeded during the design process (by analogy with the field of control theory, these would be referred to as semi-automated decisions, or rapid interventions). In most cases, the current state-of-practice operates at that second level. On the top level, multi-attribute information is gathered and used to make decisions. The decision systems effectively rely on advanced technical-organizational-socioeconomic information (by analogy with the field of control theory, this would be called adaptive control). Because it is derived from the field of control theory, this general framework is equally applicable to individual systems, combination of systems, and communities. The systems diagram presented in Figure 4 is the basic expression of the concepts embedded in this framework.

Without going through all the steps of the diagrams, key steps include gathering of information through monitoring, sensing and other field activities, processing the information through information models to determine system fragility (performance) with which the losses and the resilience performance are determined based on distinct resilience performance criteria, using estimations (based on post-event prediction) or evaluations (based on post-event data), decision support systems that consider the resiliency measures and targets, and advanced technologies (for preparedness and/or recovery) to modify the facility system or community to enhance resiliency as appropriate. The closed loops indicate that an iterative dynamic process is required to achieve optimal response.

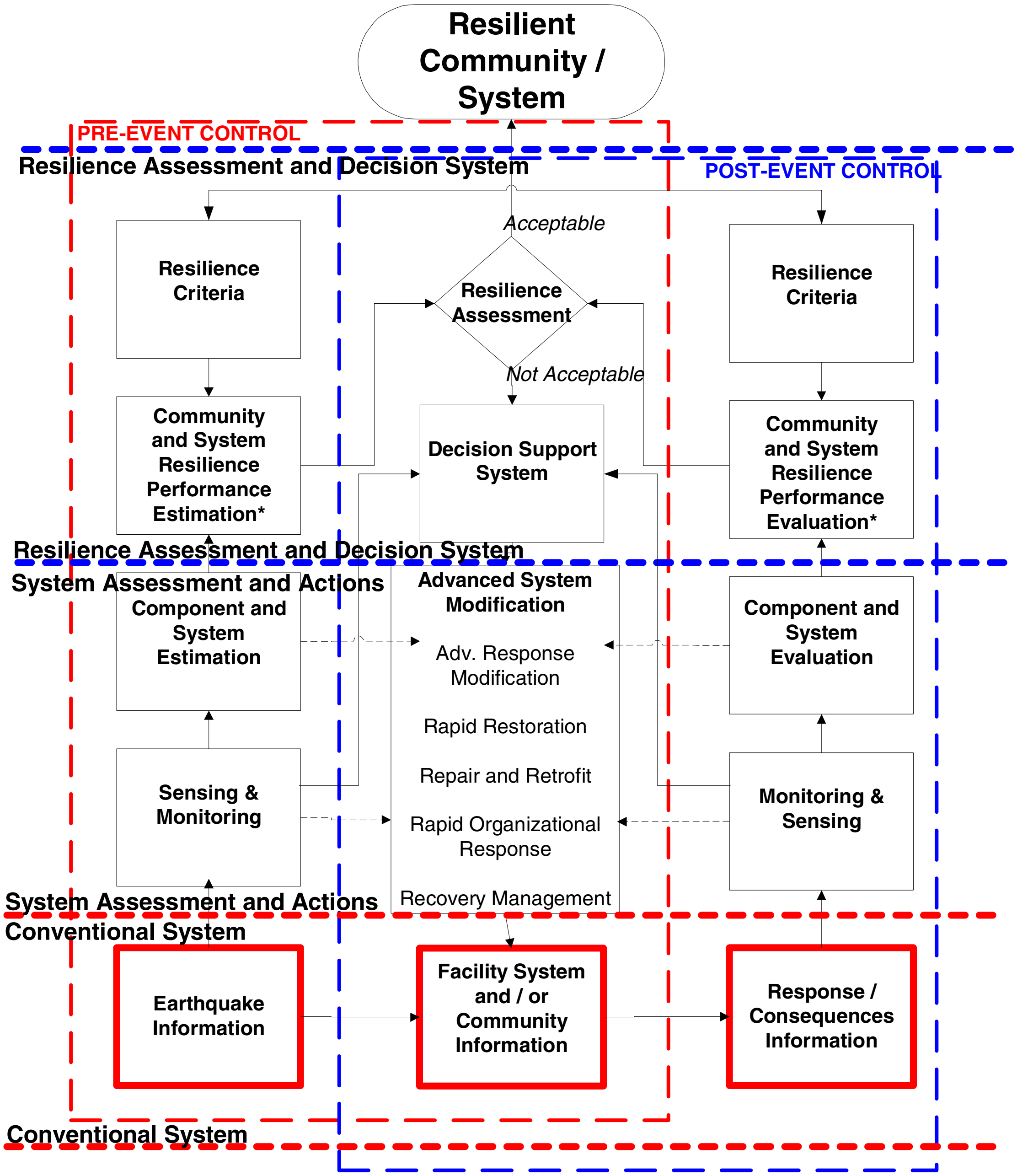

Figure 4. Systems diagram: schematic level of details.

CONCLUSIONS

This paper presented a framework for defining seismic resilience and specifying quantitative measures of resilience that can serve as foci for comprehensive characterization of the earthquake problem to establish needs and priorities. The keys to this framework are the three complementary measures of resilience: "Reduced failure probabilities," "Reduced consequences from failures," and "Reduced time to recovery." Dimensions of resilience, examples of which have been discussed here, include the quantitative measures of the "ends" of robustness and rapidity, as well as the "means" of resourcefulness and redundancy. The framework integrates those measures into the four dimensions of community resilience — technical, organizational, social and economic — all of which can be used to quantify measures of resilience for various types of physical and organizational systems. Systems diagrams then establish the tasks required to achieve these objectives.

This framework makes it possible to assess and evaluate the contribution to seismic resilience of various activities (including research), whether focusing on components, systems, or organizations, with applications ranging from lifelines and building systems to the organizations that provide critical services. Well-defined and consistently applied quantifiable measures of resilience make it possible to carry out various kinds of comparative studies (e.g., to assess the effectiveness of various loss-reduction measures, such as structural and nonstructural retrofit systems), to determine why some systems are more resilient than others, and to assess changes in system resilience over time. The ultimate objective of this work is to make the concepts that are presented in this paper adaptable for the analysis of various critical infrastructure elements (both as individual systems and as interrelated sets of systems) exposed to both natural disasters and disasters resulting from accidents or premeditated acts of violence.

ACKNOWLEDGMENTS

This work was supported in whole by the Earthquake Engineering Research Centers Program of the National Science Foundation under Award Number ECC-9701471 to the Multidisciplinary Center for Earthquake Engineering Research. The authors also thank Ralph L. Keeney (University of Southern California) for his valuable contributions. However, any opinions, findings, conclusions, and recommendations presented in this paper are those of the authors and do not necessarily reflect the views of the sponsors.

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APPENDIX A – EXAMPLES OF RESILIENCY MEASURES

Table A1. Center wide (global) performance measures (illustrative)

PERFORMANCE CRITERIA				
PERFORMANCE MEASURES	Robustness	Redundancy	Resourcefulness	Rapidity
TECHNICAL	Damage avoidance and continued service provision	Back-up/duplicate systems, equipment and supplies	Diagnostic and damage detection technologies and methodologies	Optimizing time to return to pre-event functional levels
ORGANIZATIONAL	Continued ability to carry out designated functions	Back-up resources to sustain operations (e.g., alternative sites)	Plans and resources to cope with damage and disruption (e.g., mutual aid, emergency plans, decision support systems)	Minimize time needed to restore services and perform key response tasks
SOCIAL	Avoidance of casualties and disruption in the community.	Alternative means of providing for community needs.	Plans and resources to meet community needs	Optimizing time to return to pre-event functional levels
ECONOMIC	Avoidance of direct and indirect economic losses.	Untapped or excess economic capacity (e.g., inventories, suppliers).	Stabilizing measures (e.g., capacity enhancement and demand modification, external assistance, optimizing recovery strategies)	Optimizing time to return to pre-event functional levels

Table A2. Technical performance measures (illustrative)

PERFORMANCE CRITERIA				
System	Robustness	Redundancy	Resourcefulness	Rapidity
GLOBAL	Damage avoidance and continued service provision	Back-up/duplicate systems, equipment and supplies	Diagnostic and damage detection technologies and methodologies	Optimizing time to return to pre-event functional levels
POWER	Maximize availability of operational power supply (units) after EQ (e.g., #% of pre-earthquake level following small earthquake)*	Replacement inventories (e.g., #% available for small earthquake)	Models to assess network vulnerability and damage (e.g., EPRI model)	Maximize provision target power supply level (e.g., restoration to 95% of pre-earthquake level within 1 day)
WATER	Maximize availability of operational water supply (units) after EQ (e.g., #% of pre-earthquake level following small earthquake)	Replacement inventories (e.g., #% available for small earthquake)	Models to assess network vulnerability and damage (e.g., SCADA)	Maximize provision of target water supply level (e.g., restoration to #% of pre-earthquake level within 1 day)
HOSPITAL	Maximize availability of buildings and equipment (units) and #% of functions operational after small earthquake) – (technical unit to be defined)	Back-up/duplicate systems, equipment and supplies (e.g., #% available for small earthquake)	Integrated fragility models to assess system vulnerability and damage	Buildings and equipment are fully functional immediately after EQ
R&R	Avoid damage and maintain functionality of critical emergency facilities (e.g., EOCs, fire and police stations)	Backup resources exist to provide services in case of loss of functionality	Damage detection technologies and methodologies, other information technologies and decision support systems.	All technology needed for command, control, coordination and critical response tasks is operational

Table A3. Organizational performance measures (illustrative)

PERFORMANCE CRITERIA				
System	Robustness	Redundancy	Resourcefulness	Rapidity
GLOBAL	Continued ability to carry out designated functions	Back-up resources to sustain operations (e.g., alternative sites)	Plans and resources to cope with damage and disruption (e.g., mutual aid, emergency plans, decision support systems)	Minimize time needed to restore services and perform key response tasks
POWER	Emergency organization and infrastructure in place; critical functions identified	Replacement inventories for critical equipment (e.g., transformers, bushings)	Plans for mobilizing supplies and personnel (e.g., mutual aid agreements); identification of emergency work-around strategies	Maximum restoration of power supply
WATER	Emergency organization and infrastructure in place; critical functions identified	Alternative water supplies available (e.g., San Francisco Auxiliary Water Supply System)	Plans for mobilizing supplies and personnel (mutual aid agreements); identification of emergency work-around strategies	Maximum restoration of water supply (potable water, fire-following, industrial usage)
HOSPITAL	Emergency organization and infrastructure in place; critical functions identified	Alternative sites and procedures identified for providing medical care	Plans and procedures for mutual aid & emergency transfer of patients to undamaged hospitals	Maximize provision of critical medical and health care services; minimize avoidable negative health outcomes
R&R	Emergency organization and infrastructure in place; critical functions identified	Intergovernmental division of labor for carrying out emergency response activities (e.g., provision of assistance of search and rescue	Emergency management plans and response strategies effectively implemented	Minimize time needed to initiate and complete critical response tasks (e.g., fire-fighting, search and rescue, activation of intergovernmental mutual aid)