The Case for Systemic Resilience: Urban Communities in Natural Disasters

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A system of systems: An urban community

A modern urban community bustles with life. We engage in work, business, entrepreneurship, education, culture and entertainment to pursue our wishes and fulfil our goals. We flock to cities that offer exciting opportunities and fulfilling experiences. As we take part and actively construct the so-called higher-level societal functions of an urban community, seldom do we observe the built environment that supports these functions (Figure 1). The roles of buildings that provide shelter, and infrastructure systems that furnish basic services of power, water, transport and communication are often taken for granted. The fundamental notion of resilience is far from the minds of average citizens… until a natural disaster strikes.

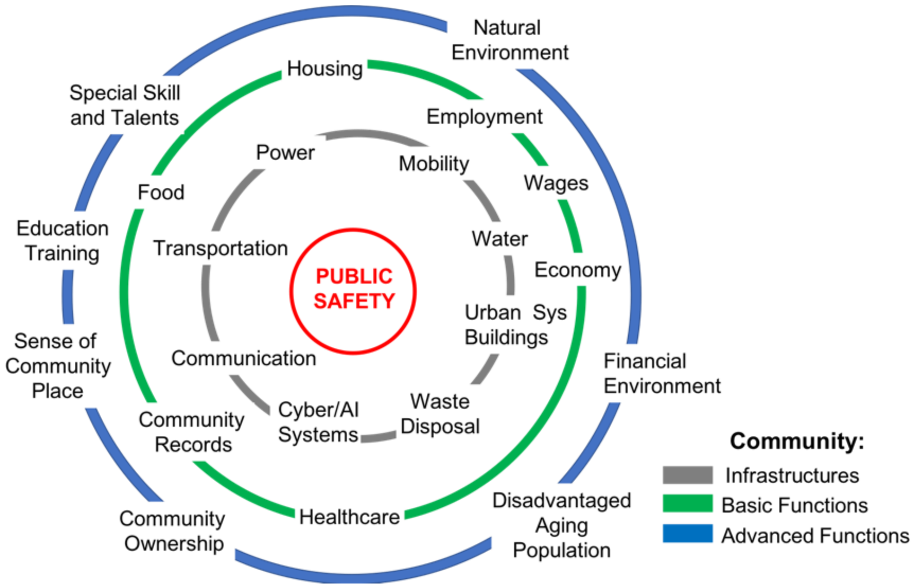

Figure 1: Urban community functions (after (Southeast Region Research Initiative (SERRI) and Community and Regional Resilience Institute (CARRI), 2009))

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The systemic nature of a modern urban community, and the need for its resilience, becomes painfully obvious in a natural disaster. Destruction of buildings crudely exposes their primary shelter functions. Failure of an infrastructure system to deliver the expected services directly affects the inhabitants and cascades to challenge other infrastructure systems as damage is absorbed. Importantly, recovery is also systemic. Re-establishing the service of one infrastructure system depends, often, on re-establishing the services of other infrastructure systems. Restoring the shelter functions for community inhabitants is slower, with building repairs and reconstruction taking more time and requiring more resources. Demand for infrastructure systems services is, in turn, directly related to the re-establishment of the shelter functions, closing another systemic dependency loop. And all this concerns only the resilience of the so-called front-line community systems, on which the re-establishment of higher-level community functions clearly depends.

Systemic resilience of urban communities to natural hazards is a process of making the community whole again or in some adapted form. Among the many definitions of resilience, some reviewed in the first volume of IRGC's Resource Guide on Resilience (https://www.irgc.org/irgc-resource-guide-on-resilience/), I find the functionality-based concept, developed within the MCEER Centre and presented by Bruneau and co-workers in (Bruneau, et al., 2003), appropriate for the built environment and the civil infrastructure systems of modern urban communities. The swoosh-shaped resilience curve they introduced is emblematic of the resilience process, while the four attributes (robustness, redundancy, resourcefulness and rapidity) framed the engineering actions available to increase the natural hazard resilience of communities, a goal aspired to by many and adopted in practice by the select pioneering cities, such as those participating in the 100 Resilient Cities network (https://www.100resilientcities.org).

Community design for resilience

Lost in the shuffle of recovery are the unrecoverable missing, dead or wounded: it is the risk of large-scale loss of life and limb that originally defined a natural disaster as a high-consequence low-probability event. Civil engineers today routinely design elements of the built environment and infrastructure systems of a community for life safety, under loads that span the gamut from permanent and known to very rare and difficult to estimate, using the principles of performance-based risk-informed design. In fact, it is because of robustness and redundancy built into the civil engineering design codes that only low-probability events have high consequences in modern communities. Thus, in the domains of risk and resilience for urban communities in natural disasters are tightly intertwined.

Great earthquake disasters of the past decade (e.g. 2010 Maule earthquake in Chile, 2011-2012 Christchurch earthquake series in New Zealand, even the 2011 Tōhoku earthquake in Japan) demonstrate that a century of seismic design focused on life safety risks and investment in modern built infrastructure paid off in terms of minimizing the casualties. On the other hand, damage to the buildings and infrastructure systems was extensive, and the recovery and rebuilding is slow and costly, straining not only the financial and material resources but also the social fabric of the affected communities. The impetus for performance-based risk- and resilience-informed design is strong: a probabilistic performance-based engineering paradigm developed within the PEER Centre by Cornell and Krawinkler (Cornell & Krawinkler, 2000) provides a framework for defining and attaining multiple design objectives. While life safety remains of ever-present concern, this framework enables simultaneous consideration of damage and design for efficient and speedy recovery. I find the resilience-based seismic design examples presented by Terzić and co-workers (Terzic, Mahin, & Comerio, 2014) particularly illustrative because they explicitly include the costs of business interruption during the recovery process in engineering decision making.

Civil engineers, however, design and build one element at a time. They are aware of systemic aspects, but the design codes and the business practices in engineering design and construction focus their attention on setting performance objectives for elements of the urban community and achieving them element by element. This is significant drawback. Extending a performance-based risk- and resilience-informed design paradigm from system element to the system level, and further, to the community system-of-systems is clearly needed (Figure 2).

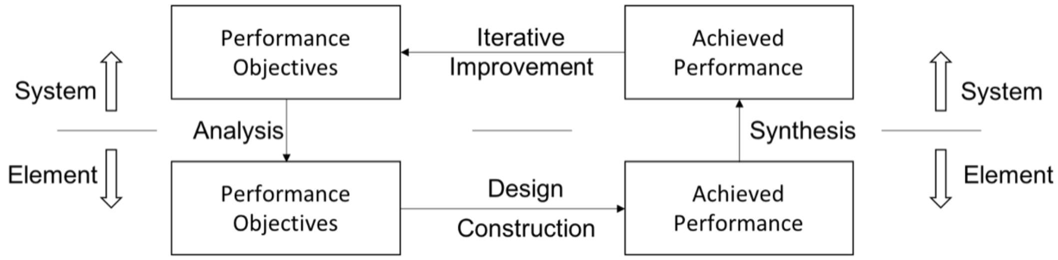

Figure 2: System- and element-level performance-based design process.

The first steps towards a systemic risk- and resilience-based urban community design have already been made. Setting system-level urban community seismic resilience objectives was explored in the San Francisco Planning and Urban Research Association Planning Resilient City project (San Francisco Planning and Urban Research Association [SPUR], 2009). There, probabilistic targets for the provision of shelter and infrastructure system functionality in a community struck by an earthquake are given in terms of several points along the recovery curves. This is crucial: it embraces the dynamic nature of the resilience process and sets out design acceptance criteria over a time horizon. De-convolving the community-level resilience objectives to the level of the community's built environment and infrastructure system elements is the next step. One way to do this using a logic tree approach borrowed from nuclear facility safety analysis was done by Mieler and co-workers (Mieler, Stojadinovic, Budnitz, Comerio, & Mahin, 2015). Given element-level resilience objectives, engineers can now design these elements considering their systemic resilience roles. To complete the design loop, the system-(community)-level behaviour of the so-designed elements must be checked and their individual and systemic resilience quantified. Composing the community systems (bottom-up, building from their elements) and quantifying their system-level resilience during the recovery time can be done using the Re-CoDeS framework (Didier, Broccardo, Esposito, & Stojadinovic, 2018). Using Re-CoDeS, or another framework for system-level resilience quantification, a community engineer can verify if the system-level community resilience goals have been achieved or not.

Our cities today

Today, urban planners and engineers seldom have a blank sheet to design urban communities from scratch. Modern urban communities are systems of systems, built upon the constructions of previous generations (i.e. legacy systems), and are continually transforming as they are being used. The built environment and the infrastructure systems are not only interlaced spatially, but are also interconnected in time, throughout their life cycle. Individual infrastructure elements and buildings age and will, sooner or later, be transformed, re-engineered or replaced. Resilient urban communities also transform with the changing needs and interests of their inhabitants, the evolving population densities and resource flows, and the (r)evolution of technologies and industries. They must also adapt to the changes in intensity and frequency of the natural disasters they may face on an even longer time scale, a challenge of climate change that urban communities are just beginning to recognize and tackle.

Systemic risk-based design against natural disasters tends to emphasize the robustness and redundancy characteristics of urban communities. This can be costly: in the era of limited resources and growing demands for them, dedicating a substantial portion to mitigate the effects of unlikely events that may happen once in a relatively distant future, means depriving the community of other more immediate needs and abandoning developments that may be more consequential in the future. Conversely, systemic resilience-based design tends to emphasize rapidity and resourcefulness of urban communities, investing future resources in effective damage absorption, speedy and efficient recovery, and agile adaptation to new conditions. While placing the burden of coping with natural disasters on future generations frees todays resources for other needs, the very real life-safety risks must still be covered today by actively maintaining the service of existing systems at the levels of function and safety needed to satisfy the community demands (for example, the recent collapse of the Morandi bridge in Genova, Italy). This risk versus resilience trade-off illustrates plastically the moral hazard facing the community decision makers.

Faced with continuous growth of risk exposure (primarily due to increase in wealth, asset concentration and urban densification) and continuous degradation of the built environment and civil infrastructure systems (primarily due to use and aging), modern urban communities must make tough decision about their natural disaster resilience. These decisions are complicated by uncertainties, not only about the likelihood and intensity of possible natural disasters but also about future directions community development may take and the long-term implications of todays' decisions that are difficult to foresee, and by constraints on the recourses a community can deploy to increase its natural disaster resilience.

Resilient communities by systemic design

There is, clearly, a need for a balanced approach to increasing the resilience of modern urban communities to natural disasters. Placing the problem solely in the context of civil engineering, even using modern risk- and resilience-based design frameworks, is not sufficiently broad. Community-level resilience objectives need to consider not only the consequences of a natural disaster, but also the means the community has to deal with them now and its willingness to postpone dealing with such consequences to the future (namely, the less risk versus more resilience conundrum). Formulating resilience design objectives, as well as resilience metrics and ways to quantify systemic community resilience, in terms useful to both civil and financial engineers is a start in the right direction. Importantly, this expands the scope of possible actions to increase the natural disaster resilience of communities from civil engineering measures to financial engineering measures and combinations thereof. For example, a community could decide to implement some robustness- or redundancy-increasing civil engineering measures now, while preparing for recovery by securing the necessary resources in the future using financial instruments available on the bond or insurance markets. Furthermore, such common resilience performance objectives and resilience metrics make it possible to rationally quantify resilience in terms of costs and benefit. This is key to making resilience-related community-level decisions, applicable over both short and long time horizons, that fully account for the life cycle lengths of the built environment and civil infrastructure system components as well as the long return periods of potent natural disasters.

Modern urban communities are complex systems of systems. They must be resilient to natural disasters today, and their natural disaster resilience must only grow and become more systemic to match community growth and meet the challenges of the future. Understanding their natural disaster resilience requires a systemic approach, considering simultaneously the system-level and element-level hazard exposures, as well as system and element risks and recovery patterns as well as interdependencies. Increasing the resilience of modern communities is a systemic effort, requiring synergistic civil and financial engineering actions, as well as consistent public policy, over a long period of time. The civil and financial engineering community is developing frameworks and tools for systemic resilience-based design, with the goal to make steering of complex community systems through transformations towards a more resilient and, ultimately, a more sustainable state possible. However, the crucial decision to implement such resilience-based community-level actions is with the citizens. It is time to make the case for systemic resilience loudly and clearly: YES, it can be done!

Annotated bibliography

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., . . . von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra, 19*(4), 733-752. This paper pioneered 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 that address failure probabilities, consequences from failures and time to recovery, and includes quantitative measures of robustness, rapidity, resourcefulness and redundancy. It integrates those measures into the four dimensions of community resilience: technical, organizational, social, and economic. This framework can be useful to determine the resiliency of elements and systems, and to develop resiliency targets and detailed analytical procedures to generate these target values.

Cornell, C. A., & Krawinkler, H. (2000). Progress and challenges in seismic performance assessment. *PEER Center News* (Spring). This two-page article in the Pacific Earthquake Engineering Research (PEER) Center newsletter outlined what became known as the PEER framework for probabilistic performance-based earthquake engineering. The concepts of intensity measure, engineering demand parameter, damage measure and decision variable were introduced then and continue to be used today. The framework centers on a total probability calculation of the mean annual frequency of exceeding a decision variable values given a structure in a certain seismic hazard environment. The key innovation is the split of the total probability integral into independent demand, damage and decision models, providing engineers a clear path to conduct probabilistic performance-based design of single elements of the community' built environment.

Didier, M., Broccardo, M., Esposito, S., & Stojadinovic, B. (2018). A compositional demand/supply framework to quantify the resilience of civil infrastructure systems (Re-CoDeS). *Sustainable and Resilient Infrastructure, 3*(2), 86-102. A novel compositional demand/supply resilience framework, Re-CoDeS (Resilience-Compositional Demand/Supply) is proposed in this paper. Re- CoDeS generalizes the concept of resilience to properly account not only for the ability of the civil infrastructure system to supply its service to the community, but also for the community demand for such service in the aftermath of a disaster. In the Re-CoDeS framework, the demand layer is associated with the evolution of the community demand, the supply layer is associated with the civil infrastructure system performance, and the system service model regulates the allocation and dispatch of service to the consumers. A Lack of Resilience is consequently observed when the demand for service cannot be fully supplied. Normalized integral and instantaneous Lack of Resilience measures are proposed to allow a direct comparison between different civil infrastructure systems at the component and system levels. Components and systems can be classified into different configurations, depending on the post-disaster evolution of the demand and supply.

Mieler, M., Stojadinovic, B., Budnitz, R., Comerio, M. & Mahin, S. (2015). A framework for linking community-resilience goals to specific performance targets for the built environment. *Earthquake Spectra, 31*(3), 1267-1283. This paper outlines a conceptual framework that can be used to explicitly link community-level resilience goals to specific design targets for individual systems and components within the built environment. The proposed framework employs tools, concepts, and procedures from the framework used to design, analyze, and regulate commercial nuclear power plants in the United States. The paper then presents a proof-of-concept example that demonstrates how to derive a consistent performance target for individual residential buildings from a community-level resilience goal. Lastly, it discusses potential applications of the proposed framework, including a critical evaluation of current building codes to verify whether their target performance objectives are compatible with community-level resilience goals.

San Francisco Planning and Urban Research Association [SPUR]. (2009). *The Resilient City: Defining what San Francisco needs from its seismic mitigation policies.* San Francisco, CA: SPUR. This paper provides a new framework for improving San Francisco's resilience through seismic mitigation policies. The framework: defines the concept of resilience in the context of disaster planning; establishes performance goals for the expected earthquake that supports this definition of resilience; defines transparent performance measures that help reach these resilience performance goals; and suggests next steps for San Francisco's new buildings, existing buildings and lifelines. The paper recognizes explicitly that the overall impact and cost of a disaster is strongly influenced by how long it takes to recover. The time needed to recover depends on the level of damage sustained by buildings, the availability of utilities, and how quickly communities can re-establish usable housing and livable environments. The paper headlines a series of reports available at https://www.spur.org/featured-project/resilient-city.

Southeast Region Research Initiative (SERRI) and Community and Regional Resilience Institute (CARRI). (2009). *Creating resilient communities: The work of SERRI and CARRI.* Oak Ridge, TN: Oak Ridge National Laboratory. SERRI and CARRI have started a campaign to understand the dynamics of community resilience since the early 2000s. A US framework to help communities anticipate the conditions after a potential disaster, mitigate the consequences, and afford a more rapid recovery was developed and implemented. The outcomes, in the form of reports and case studies, are available to community leaders and policy makers through the http://www.resilientus.org web site. This report gives a comprehensive summary of the decades-long work of SERRI and CARRI.

Terzic, V., Mahin, S. A., & Comerio, M. (2014, June). Comparative life-cycle cost and performance analysis of structural systems. *Proceeding of the 10th National Conference on Earthquake Engineering*. Otherwise identical buildings with different lateral load resisting structural systems behave very differently in earthquakes. Their initial cost is different. During earthquakes they incur different damage and repair costs, take different amounts of time to repair and thus cause different monetary losses due to business interruption. A comparison of life-cycle costs of these buildings under the same seismic hazard conditions was done using the FEMA P-58 framework. It revealed that structural systems with seismic base isolation are superior in their seismic performance resulting in a significant reduction of life-cycle costs despite the larger initial investment to construct them.