

Enhancing the Resilience of Communities against Extreme Events from an Earthquake Engineering Perspective

Michel BRUNEAU
Director,
Multidisciplinary Center
for Earthquake
Engineering Research
Professor, Department of
Civil Engineering
University at Buffalo
Buffalo, NY 14261
bruneau@buffalo.edu



Michel Bruneau is conducting research on the seismic evaluation and retrofit of existing steel bridges, steel buildings, and masonry buildings. He has published over 200 technical publications as a result of this research, and has co-authored the book "Ductile Design of Steel Structures" published in 1997 by McGraw Hill. He has also received many awards for his research and publications.

Summary

This paper reviews a resilience concept developed for earthquake engineering but broadly applicable to the multiple hazard, highlights some of the solutions and the opportunities afforded by existing advancements and developments made in the field of earthquake engineering to address some of the above needs, and provides an overview of modifications possible to some of these tools to help address the broader extreme event and multi-hazard problems.

Keywords: Multi-hazard, extreme events, earthquake engineering, resilience, pre-event, post-event, infrastructure.

1. Introduction

The value of focusing efforts to enhance the resilience of infrastructure against extreme events (natural disasters, technological disasters, and acts of terrorism against our society) has been long recognized, and has certainly risen in recent years following an increase in the threat from terrorism. To address this emerging need, a substantial research effort will be needed. The development of innovative and integrated solutions toward this goal will benefit from the input from experts from a large number of various disciplines.

In that perspective, some research results from the field of earthquake engineering could be modified to contribute to this objective. Earthquake engineering research has provided practical solutions to address the needs for: (i) Risk and vulnerability assessment, including the development of risk and vulnerability assessment methodologies, to prioritize the allocation of limited resources; (ii) System analysis and design, to investigate the ultimate behavior of systems and foster capacity-design principles for fail-safe outcomes; (iii) Improved materials, to enhance the ability of infrastructure components and systems to withstand hazards; (iv) Sensing technologies, for structural health monitoring, with possible applications for detection, surveillance and prevention; (v) Post-event assessment, including the use of remote sensing (airborne or satellite-based) to rapidly locate areas impacted by a disaster, the type of damage suffered, and rapid assessment of losses; (vi) Post-event on-site screening methodologies, to assess safety of structures after an event using simple tools based on expert knowledge; (vii) Advanced technologies for repair and restoration following an event, or retrofitting prior to an event; (viii) Evaluation test-beds, to test and validate new technologies proposed to achieve the above objectives.

The objective of this paper is to review a resilience concept developed for earthquake engineering but broadly applicable to multiple hazards, to highlight some of the solutions and opportunities afforded by existing advancements and developments made in the field of earthquake engineering to address some of the above needs, and to overview modifications possible to some of these tools to help address the broader extreme event and multi-hazard problems. Due to space constraints, focus here will be on selected strategies applicable prior-to-events and post-events (e.g. excluding during-event strategies, such as system health monitoring and intelligent damage detection).

2. Definition of Resilience

As part of the conceptualization of a framework to enhance the seismic resilience of communities [1], 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). 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 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:

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

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.

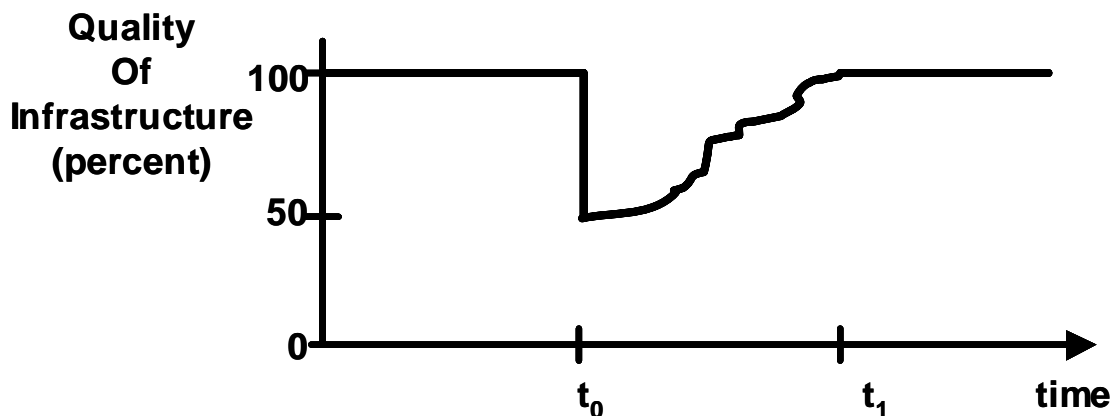


Fig. 1: Schematic representation of seismic resilience concept [1]

Due to the complexity of acute care facilities, and depending on the extent of seismic deficiencies in any specific hospital, considerable investment may be required to ensure that an acute care facility remains operational following an earthquake. The extensive resources that would be required to achieve such a level of resilience would likely not be available at the onset, and activities to upgrade the facilities would have to be staggered over many years. Ideally, using the limited resources available at any time along this multi-year upgrading process, the objective would be to first make the investments that provide the largest enhancements to seismic resilience, and to sequence all subsequent investments following the same logic. This approach presents a significant challenge to

decision makers and their specialist consultants, as there is no integrated tool that could support such a decision on factual engineering data. Integrated coordinated research is needed to investigate how such integration could be achieved.

Such a research program has been structured focusing efforts on the development of seismic response modification technologies to provide data that can be used in integrated decision engines [2,3,4]. It also addresses research needs for seismic retrofit technologies to provide effective solutions for acute care facilities, and complement the research needed to formulate the integrated decision systems that would be required to identify the most appropriate seismic actions, taking into account both engineering issues and organizational constraints (technical and organizational dimensions of resilience).

An example of “roadmap” needed to quantify and enhance the seismic resilience of acute care facilities is shown in Fig. 2. It has been constructed recognizing that past earthquakes, as well as engineering experience, have demonstrated that functionality of a building can be lost due to structural failure, geotechnical failure, or damage to nonstructural building components (i.e., medical equipment), and the fact that some of these are closely inter-related (damage to nonstructural building components is directly tied to structural response – for example, modifying structural response solely for the purpose of reducing damage to the structure may have positive or negative impacts on the seismic performance of nonstructural building components). A coordinated research program on that topic must also focus on the integrated issues of performance, including both structural and nonstructural systems and components and their functionality.

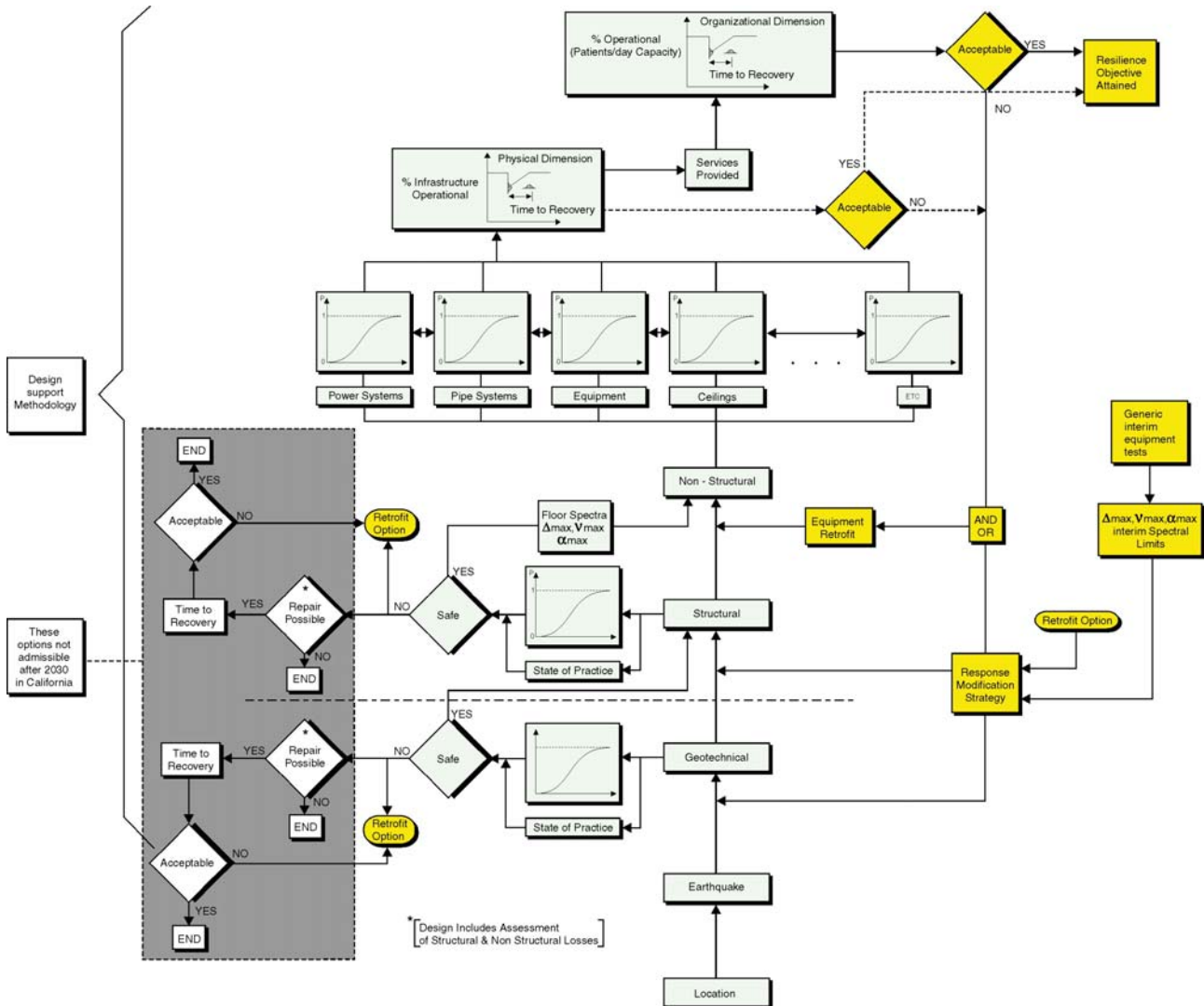


Fig. 2 Roadmap to Seismic Resilience for Acute-Care Facilities

This roadmap can serve as the backbone of the needed research activities and as a primary tool to focus and integrate research activities in this perspective, listing the steps toward the objective, and the essential dependencies. The roadmap emphasizes that seismic resilience may be compromised by failure of both engineered and non-engineered systems. It also conceptually illustrates the probabilistic fragility framework that must be integrated to quantify seismic resilience of acute care facilities, and where interventions can be made to enhance this resilience [2,3,4].

As shown in Fig. 2, a first interim quantification of resilience is possible at the physical dimension level. From there, social science research input is needed to generate the knowledge to elevate the resilience quantification to the organizational dimension level by translating the physical system resilience into operational consequences.

3. Examples of Pre-Event Technologies Applicable to Multiple Hazards

3.1 Software for Seismic Risk Analysis of Highway Systems

A new methodology for deterministic and probabilistic seismic risk analysis of highway systems has recently implemented into a public-domain software package named REDARS (Risks from Earthquake Damage to Roadway Systems) [5]. Post-earthquake functionality of highway networks is assessed based on such characteristics as network configuration, location of individual components within the overall system and specific links and subsystems, and the locations, redundancy, and traffic capacities of the links between key origins and destinations within the system. Consideration of the importance of each component to the overall system performance can provide a rational basis for establishing seismic strengthening priorities, defining seismic design strengthening criteria, effecting emergency lifeline route planning, estimating economic impact due to component or system-wide damage. It can also provide real-time information to emergency response efforts. This methodology provides an assessment of highway system seismic performance issues, and a mechanism to estimate system-wide direct losses and indirect losses due to reduced traffic flows and/or increased travel times. The California Department of Transportation (Caltrans) has initiated a trial study to apply REDARS to a region of the Bay Area Highway Network. The expansion of such a software platform to address other hazards is possible.

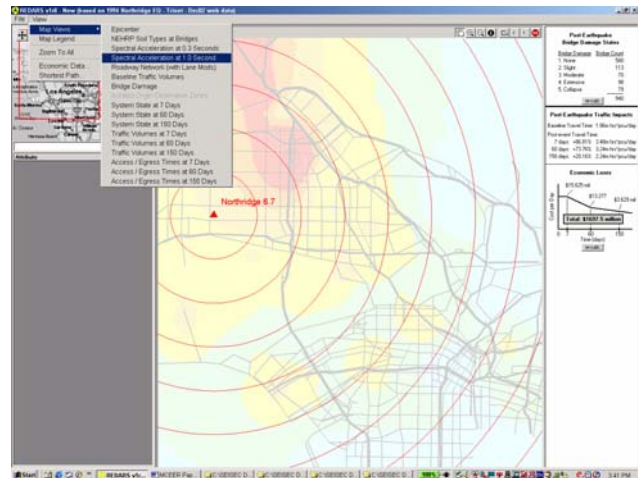


Fig. 3 REDARS graphic interface (S. Werner)

3.2 Comparing and Contrasting Natural and Human-Induced Disasters

Following the events of September 11, 2001, a multidisciplinary team visited the disaster site to focus on the collection of perishable data on the impacts of the attacks on structures, the inter-organizational management of the emergency response, and the use of new and emerging technologies in response and recovery activities [6,7,8,9]. The WTC case study is significant in several respects. First, the analysis of data that emerged is resulted in advances in both the conceptualization and quantification of a community's resilience to disasters. Secondly, although the



Fig.4 World Trade Center Disaster

incident was a consequence of intentional human action, research on the WTC is yielded both engineering and social science knowledge that can be translated to address the impact of major urban earthquakes. It is expected that it will provide an opportunity to transfer the lessons learned to improve overall disaster mitigation, preparedness, response and recovery. Furthermore, a workshop held in 2002 allowed to identify the potential commonalities between blast engineering research and earthquake engineering research, examining potential advancements for these respective communities [10].

3.3 Response Modification Systems

There currently exists a large “technology portfolio” of candidate approaches for the seismic retrofit of existing structural and non-structural systems (passive, active, and semi-active energy dissipation devices, base isolations systems, and other structural control technologies for example – some of which are described in [2,3,4]). Emerging technologies also are constantly expanding this portfolio. Research and development will allow to assess which of these technologies can prove adequate and cost-effective for protection against other hazards. It is important to recognize that some effective solutions are likely to encounter societal resistance against their implementation. Hence, the diversity of available solutions is beneficial to tackle complex loss reduction challenges related to the multi-hazard environment; it allows flexibility to rapidly adjust when changes in the societal environment alter stakeholder receptivity or attitudes about what constitute acceptable solutions to various aspects of the earthquake problem.

Retrofitting structures using seismic response modification technologies has also made it possible to harmonize the performance of structural and non-structural components for facilities to meet or exceed specified resiliency levels during and after an earthquake. Further research is needed to identify which synergistic modification technologies can be applicable with some modifications to other types of hazards. These approaches must be aimed at providing fragility data for coupled structural and non-structural components for various seismic response modification technologies.

4. Examples of Post-Event Technologies Applicable to Multiple Hazards

4.1 Remote Sensing for Damage Assessment

Assessing damage and disruption and prioritizing response resources are perhaps the most significant challenges facing emergency managers in the aftermath of major disasters. Rapid impact and damage assessment - for example, the identification of collapsed structures - is especially critical because research on earthquake mortality and morbidity indicates that death tolls rise following earthquakes unless trapped victims can be found and extricated in a timely manner [11]. Rapid and accurate situation assessment also helps emergency managers to better estimate impacts and allocate resources to areas of greatest need. Recognizing that remote sensing technologies can make a major contribution to improving post-disaster damage and situation assessment, researchers have investigated post-earthquake damage assessment using a range of remote sensing techniques, including synthetic aperture radar and moderate resolution optical imagery. Researchers have been investigating the use of high-resolution QuickBird imagery in post-disaster reconnaissance in the December 2003 Bam earthquake, and portability of this approach with the Hurricane Charley disaster, and the Indian Ocean Tsunami of December 2004. The increasing availability of high-resolution images and improved potential for collecting data in near-real-time (e.g., through the use of unmanned airborne vehicles) are making even more significant advancements possible. Remotely-sensed data are now being used in the development of new tools, such as the VIEWS (Visualizing Earthquake Impacts With Satellite Imagery) system [2,3,4], and deployed following various disasters.

Regional Damage Assessment Based on Remote-Sensing: Iran 2003



Fig.5 Damage assessment (from R. Eguchi [2])

4.2 Empirically-Based Recovery Decision Support Tools

The recovery process following disasters is not well understood. The vast majority of research on disaster recovery consists of case studies of individual communities or, at best, small groups of communities, and studies focusing on recovery processes and outcomes for particular social units, such as households. While written guidance on the recovery process does exist, for example in the form of checklists and “lessons learned” for community leaders, this type of material is also limited in both scope and empirical support. To address the need for guidance that is both comprehensive and based on solid research findings, researchers have undertaken the ambitious task of developing a comprehensive simulation model for community disaster recovery [2,3,4]. As a result, it is now possible to both analyze and visualize interactions among infrastructure, household, neighborhood, and business impacts and recovery and to determine how both pre- and post-disaster decisions (e.g., decisions to mitigate lifeline damage, decisions made regarding transportation system restoration or aid to businesses) affect longer-term losses and recovery outcomes. Refinements of the model are underway. This will make it possible for community decision makers, for the first time, to understand interrelationships and interdependencies among elements in the recovery process and make informed choices concerning alternative recovery strategies. The applicability of this approach to multi-hazard problems is a logical extension.

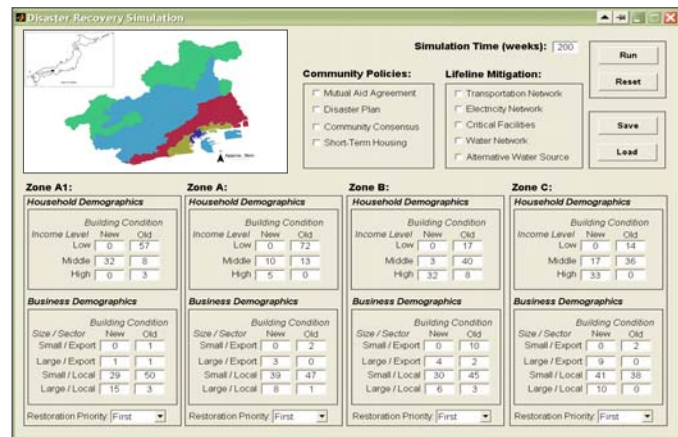


Fig. 6 Community systems (from S. Chang [3])

5. Strategy towards Multi-hazard Integration

The opportunities created by the many similarities that exist in the preparedness, response, and recovery needs for a variety of hazards provide a framework that can answer the research needs for a broad range of extreme events, particularly through the strategic alliances of various groups and research centers. As has been frequently emphasized in recent years, multi-hazard approaches may provide the framework needed for a broader nationwide implementation of strategies to enhance resilience against any specific hazard. In a structural engineering perspective, blast is the extreme event whose impact on infrastructure most closely resembles that from earthquakes (although important differences are recognized). In the perspective of using remote sensing to identify damage over broad geographical areas, tools developed for post-earthquake response could be modified to serve post-hurricane needs.

The inter-relationship between various types of disasters, the impacted infrastructure, and the type of technologies that can be used to enhance resilience of this infrastructure against extreme events is schematically shown by the cube in Figure 7. This three dimensional representation captures important research aspects as one dimension of the problem, the type of infrastructure for which these issues must be considered as another dimension, and the various hazards that must be considered as a third dimension. The intersections between hazards, research and infrastructure type define selected problems. Considering multiple hazards simultaneously effectively both expands the scope and the complexity of these problems, while ensuring the search for solutions with a broader reach. The challenges are to identify which of the technologies can be best tackled simultaneously to serve the broadest possible multi-hazard protection agenda, to discover which natural synergies exist across this 3-D space, and to construct multidisciplinary teams that can research and develop the needed integrated solutions.

A multi-disciplinary team approach makes it possible to view and address the above issues through coordinated and integrated research activities, by development of the advanced knowledge and technologies needed to achieve integrated engineering tools, decision-support systems, and related techniques, and procedures that can provide cost-effective quantitative enhancement of seismic resilience of these highly critical structures and systems.

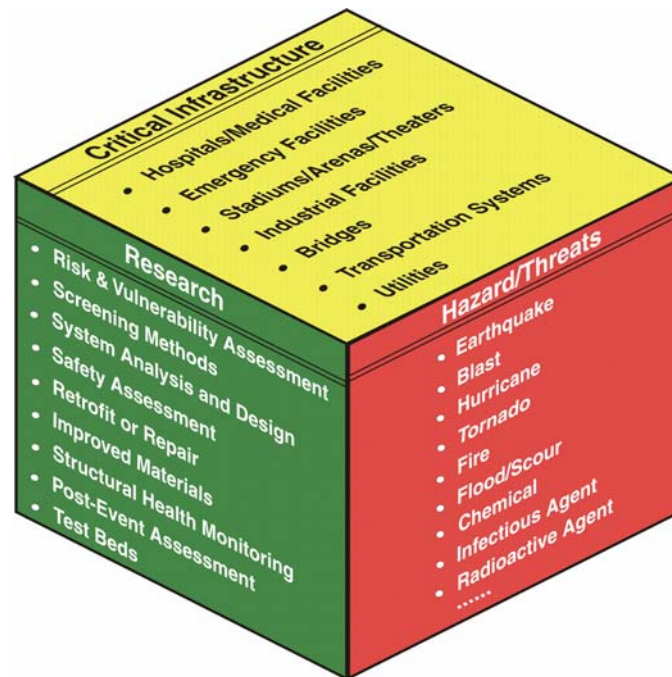


Fig. 7: Research, Infrastructure, and Hazards (adapted from G. C. Lee, personal communication)

6. Conclusions

Much promise exists to enhance the resilience of communities against various extreme events by expanding on the knowledge generated to address the earthquake engineering problems over the past decades. The recently developed resilience concept is broadly applicable to the multiple hazards, as well as some of the existing solutions developed to mitigate earthquake risks. However, it is believed that a multi-disciplinary team approach is necessary to provide the coordinated and integrated research strategies towards that objective.

7. Acknowledgments

This research was supported in part by the Earthquake Engineering Research Centers Program of the National Science Foundation (NSF) under Award Number EEC-9701471, and by the Federal Highway Administration under contract DTFH61-98-C-00094, to the Multidisciplinary Center for Earthquake Engineering Research (MCEER). The author also thanks Stuart Werner (Seismic Systems & Engineering Consultants), Ron Eguchi (ImageCat Inc), Stephanie Chang (University of British Columbia) and George Lee (University at Buffalo) for contributing to this paper figures from their MCEER research activities. However, any opinions, findings, conclusions, and recommendations presented in this report are those of the authors and do not necessarily reflect the views of these individuals or of the sponsors.

8. References

- [1] Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., von Winterfelt, D., (2003). "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities", EERI Spectra Journal, Vol.19, No.4, pp.733-752.
- [2] MCEER (2004). "Research Progress and Accomplishments", Multidisciplinary Center for earthquake engineering research, University at Buffalo, Buffalo, NY <http://mceer.buffalo.edu/publications/resaccom/0304/default.asp>
- [3] MCEER (2003). "Research Progress and Accomplishments", Multidisciplinary Center for earthquake engineering research, University at Buffalo, Buffalo, NY



<http://mceer.buffalo.edu/publications/resacom/0103/default.asp>

- [4] MCEER (2002). “Research Progress and Accomplishments”, Multidisciplinary Center for earthquake engineering research, University at Buffalo, Buffalo, NY
<http://mceer.buffalo.edu/publications/resacom/0001/default.asp>
- [5] Werner, S.D., Taylor, C.E., Moore, J.E., Walton, J.S., Cho, S. (2000). “A Risk-Based Methodology for Assessing the Seismic Performance of Highway Systems”, Report MCEER-00-0014, Multidisciplinary Center for earthquake engineering research, University at Buffalo, Buffalo, NY.
- [6] Bruneau, M., Whittaker, A., Reinhorn, A., (2002). “Engineering and Organizational Issues Related to the World Trade Center Attack, Volume 1, Overview of Damage to Buildings Near Ground Zero”, MCEER Special Report - MCEER-02-SP02, Multidisciplinary Center for earthquake engineering research, University at Buffalo, Buffalo, NY.
- [7] Berman, J., Warn, G., Whittaker, A., and Bruneau, M., (2002). “Engineering and Organizational Issues Related to the World Trade Center Attack, Volume 2, Reconnaissance and Preliminary Assessment of a Damaged Building Near Ground Zero.”, MCEER Special Report - MCEER-02-SP03, Multidisciplinary Center for earthquake engineering research, University at Buffalo, Buffalo, NY.
- [8] Huyck, C.K., Adams, B.J. (2002). “Emergency Response in the Wake of World Trade Center Attacks: The Remote Sensing Perspective”, MCEER Special Report MCEER-02-SP05, Multidisciplinary Center for earthquake engineering research, University at Buffalo, Buffalo, NY.
- [9] Lee, G.C., Rzhnevsky, V., Tong, M., Chen, S., “From the WTC Tragedy to the Development of Disaster Engineering for Landmark Buildings – An Extension of the Performance-based Earthquake Engineering Approach”, MCEER Special Report MCEER-03-SP04, Multidisciplinary Center for earthquake engineering research, University at Buffalo, Buffalo, NY.
- [10] MCEER (2002). “Proceedings of the Workshop on Lessons from the World Trade Center Terrorist Attack: Management of Complex Civil Engineering & Terrorism-Resistant Civil Engineering Design”, Bruneau, M., editor, MCEER Special Report MCEER-02-SP08, Multidisciplinary Center for earthquake engineering research, University at Buffalo, Buffalo, NY, 172 pages (accompanied by 2 CD-ROMs).
- [11] Noji, E. (Ed.) 1997. “The Public Health Consequences of Disasters”. New York: Oxford University Press.