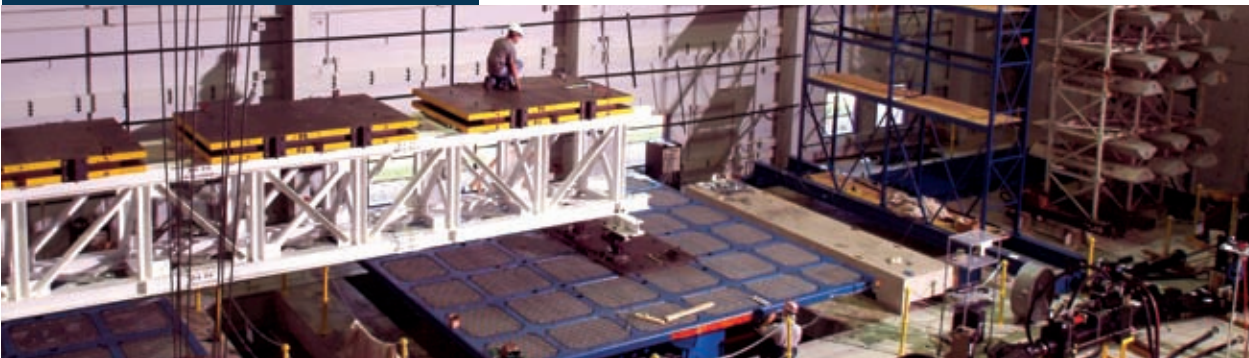


# ENGINEERING RESILIENCE SOLUTIONS

From Earthquake Engineering  
to Extreme Events



1997-2007

A Decade of Earthquake Engineering  
and Disaster Resilience



## Photo Credits

Most of the photographs and illustrations in this report were provided by MCEER investigators, staff members, or strategic partners. We greatly appreciate these contributions. In addition, the bottom cover photo and the photo of Michel Bruneau on page 2 were taken by Douglas Levere, University at Buffalo.

## About this Publication

This publication was developed to celebrate the accomplishments of MCEER during its funding as part of the Earthquake Engineering Research Centers (EERC) program of the National Science Foundation (NSF). It provides an overview of MCEER's earthquake engineering and disaster resilience accomplishments from 1997-2007. The research efforts, built on the solid foundation provided by the National Center for Earthquake Engineering Research (NCEER) during its first 10 years of funding in the Civil and Mechanical Systems Division of NSF, have made a measurable impact on advancing knowledge, education, technology and industrial competitiveness of the engineering workforce and its diversity. Collectively, the various activities of this program have contributed to preparing communities to be more resilient against earthquakes, and by extension, against multiple hazards. Descriptions of the impacts from other MCEER research initiatives, including a significant research program funded by the Federal Highway Administration since 1992, are available on the extensive MCEER website at <http://mceer.buffalo.edu>.

*The work reported herein was supported primarily by the Earthquake Engineering Research Centers Program of the National Science Foundation under NSF Award Number EEC-9701471 to MCEER. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of the National Science Foundation.*

**December 2008 ■ MCEER-08-SP09**

Jane Stoyke - Managing Editor

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# ENGINEERING RESILIENCE SOLUTIONS

## *From Earthquake Engineering to Extreme Events*

**1997-2007**

### **A Decade of Earthquake Engineering and Disaster Resilience**

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# DIRECTOR'S MESSAGE

## *The Promise Ahead: Earthquakes to Multiple Hazards & Extreme Events*

Making our society more resilient to disasters is a complex endeavor, for which there are no quick fixes. Many questions remain unanswered and a myriad of problems remain unsolved. However, one thing is certain - finding solutions to this challenge requires a concerted effort and the marshalling of talents across a wide range of disciplines.

In the broader multi-hazard picture, the nation stands today approximately where it was a few decades ago when it began seeking ways to reduce the loss of life and property caused by earthquakes. This effort started with a recognition that much of the country's urban centers, structures, and infrastructure were located in areas at risk to moderate or severe seismic activity. There was a need for research to mitigate the vulnerability of these assets and prevent potentially devastating impacts on the nation. Then, like today, cost-effective solutions to the problems posed by earthquakes required more than engineering alone. They required a coordinated, unified effort of stakeholders from various disciplines.

*"MCEER has pioneered multidisciplinary earthquake engineering research and a culture of coordinated large-scale integrated research projects"*

In response to this challenge, as a national earthquake engineering research center funded by the National Science Foundation, MCEER pioneered multidisciplinary research and a culture of coordinated large-scale integrated projects – all geared towards enhancing the seismic resilience of communities. These, in turn, have led to many advances in knowledge and accomplishments that have had a tangible impact on practice.



*Michel Bruneau, MCEER Director : 2003-2008*

This report highlights many of these advances, illustrating how MCEER's integrated team of researchers, facilities and research partners in academia, industry and government, has developed

*"The Center is looking forward to continuing to serve the NEHRP mission for many years to come"*

and delivered solutions to address the challenges that earthquakes pose to our way of life. As such, the pages that follow showcase MCEER's ability to mobilize expert multidisciplinary teams to investigate, test and develop strategies and technologies that lessen impacts of earthquakes. Additionally, they show how MCEER's research is fulfilling its vision to achieve disaster resilient communities through research, education and technology transfer. Fundamentally, this is accomplished through MCEER's resilience framework which quantifiably strives to reduce probability of failures in systems and infrastructure, to reduce consequences due to failure, and to reduce recovery time for key facilities and organizations whose functions are essential for community well-being after an earthquake and/or other disaster. These critical facilities include water and power lifelines, acute care facilities (hospitals), bridges and highways,



and organizations that are responsible for emergency management at the local community level.

This report also provides a promising glimpse of the future. Many of the solutions developed by MCEER for earthquake hazard mitigation and response can be extended to address threats from other natural and man-made disasters. Toward this end, MCEER has expanded its vision to the development of engineering systems that aid at-risk communities in establishing infrastructure that is resilient against a broad spectrum of extreme events including multiple natural disasters, technological disasters, and acts of terrorism against our society. MCEER activities are already underway in support of this broader vision of helping establish *disaster resilient communities*.

*MCEER's white paper explores research initiatives to be undertaken in a multi-hazard perspective.*



Our nation's leadership has already identified a number of Grand Challenges for Disaster Reduction,<sup>1</sup> and many of these can be met through problem-focused, solutions-oriented multidisciplinary, multi-institutional, research – the type for which MCEER is recognized in the engineering community.<sup>2</sup> Fueled by the political resolve to enhance our nation's disaster resilience, future research should focus on solutions, integrated across multiple hazards, to mitigate the impact of various extreme events on critical facilities and lifelines – the key



Mosqueda and Porter, MCEER-07-SP03

*Structural damage observed following Hurricane Katrina was similar to damage caused by earthquakes.*

infrastructure systems whose failure most readily results in disruption, hardships, and losses, during and following disasters. MCEER's tradition of spearheading and/or embracing innovative ideas and nurturing them from initial fundamental research to implementation through the efforts of high caliber researchers and strategic partners, provides one platform towards achieving this goal.

The objective to achieve a synergy of solutions across the continuum of hazards is something that has just barely begun to be exploited or even investigated. MCEER plans to be at the forefront of this effort, while continuing to serve the mission of the National Earthquake Hazards Reduction Program (NEHRP) for decades to come.

**Michel Bruneau**

MCEER Director: 2003-2008

**NOTE:** While this report focuses on the MCEER accomplishments related to activities funded by the EERC Program of NSF from 1997 to 2007, the Center has a track record of relevant research, education and outreach activities for many other sponsors. For example, MCEER's on-going research and outreach on the *Seismic Vulnerability of Highway Systems*, funded by the Federal Highway Administration (FHWA), equals in accomplishments and size that of the NSF-funded project. Refer to the MCEER website (<http://mceer.buffalo.edu>) for details on other MCEER research programs. Finally, although only a sampling of the work conducted could be included here due to space limitations, the list of technical reports included at the end of the report provides for more in-depth reading.

<sup>1</sup> Subcommittee on Disaster Reduction (2005). **Grand Challenges for Disaster Reduction**, National Science and Technology Council, Committee on Environment and Natural Resources, June 2005.

<sup>2</sup> Bruneau, M., Filiatrault, A., Lee, G.C., O'Rourke, T.D., Reinhorn, A., Shinozuka, M. and Tierney, K., (2005). White Paper on the **SDR Grand Challenges for Disaster Reduction**, A commentary on: **Grand Challenges for Disaster Reduction**, MCEER-05-SP09, December 2005, available at [http://mceer.buffalo.edu/publications/white\\_papers/05-SP09/default.asp](http://mceer.buffalo.edu/publications/white_papers/05-SP09/default.asp).



# A FRAMEWORK FOR DISASTER RESILIENCE

## *Resilience Concept Drives Development of New Knowledge, Tools & Technologies*

MCEER's research activities are predicated on the notion that improvements in resilience are achieved through the application of advanced technologies and decision tools in both the pre- and post-extreme event context. Research activities seek to obtain quantitative data on the extent to which these measures result in improvements in resilience for infrastructure systems, hospitals, and communities and to explore their impacts in test-bed studies.

### **Vision Statement:**

*The ultimate vision of the Multidisciplinary Center for Earthquake Engineering Research (MCEER) is to help establish earthquake resilient communities.*

### **Mission Statement:**

*The overall goal of MCEER is to enhance the seismic resilience of communities through improved engineering and management tools for critical infrastructure systems (water supply, electric power, and hospitals) and emergency management functions. Seismic resilience (technical, organizational, social, and economic) is characterized by reduced probability of system failure, reduced consequences due to failure, and reduced time to system restoration.*

At the foundation of all of MCEER's efforts is the concept of Disaster Resilience, which provides the basis to:

- Quantifiably assess a current state of resilience
- Set specific objectives to improve upon it, and
- Establish remedial tasks and measure progress toward meeting pre-determined resilience targets.

The objectives of enhanced Disaster Resilience are to minimize loss of life, injuries, disruption of important services, and economic losses; in short, to minimize any reduction in quality of life due to disaster.

## **Definition & Quantification of Disaster Resilience**

Disaster resilience is the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters, and carry out recovery activities in ways that minimize social disruption, while also mitigating the effects of future

disasters. Consequently, strength, flexibility, and the ability to cope with and overcome extreme challenges, are the hallmarks of disaster-resilient communities.



## Characteristics of Resilience

Inherent in the definition of disaster resilience are a number of characteristics that help to make it more tangible and measurable. Specifically, disaster resilience is characterized by:

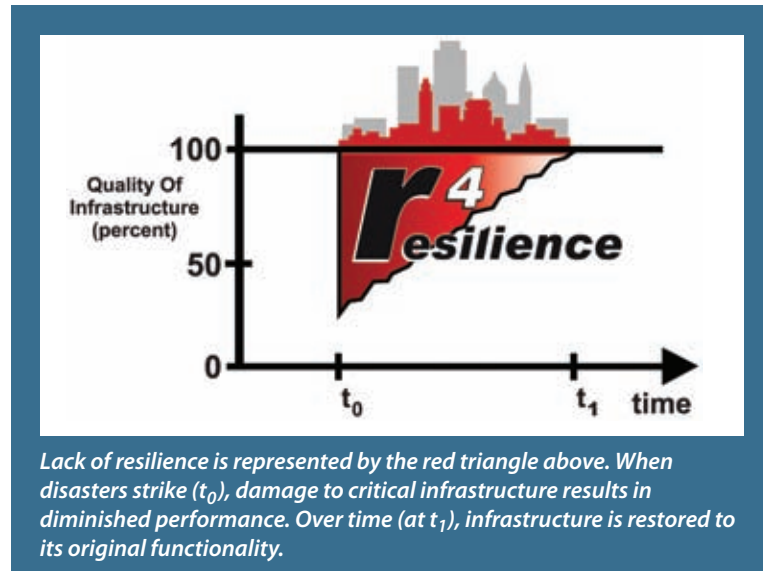
- **Reduced failure probabilities** – i.e., the reduced likelihood of damage & failures to critical infrastructure, systems and components;
- **Reduced consequences from failures** – in terms of injuries, lives lost, damage and negative economic and social impacts; and
- **Reduced time to recovery** – the time required to restore a specific system or set of systems to normal or pre-disaster levels of functionality.

Based on these characteristics, resilience can be enhanced by reducing the likelihood of failures to critical infrastructure (thereby, reducing their impacts) and speeding the time to recovery.

## Properties of Resilience: The Four “Rs”

In an effort to enhance these characteristics, MCEER’s concept of disaster resilience considers four fundamental properties. They are:

- **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 function;
- **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 supply material - i.e., monetary, physical, technological, and informational - and human resources to



meet established priorities and achieve goals); and

- **Rapidity** – the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

MCEER’s research program focuses on improvements in robustness and redundancy of critical infrastructure via advanced structural control and other technologies. It likewise addresses characteristics of resourcefulness and rapidity through development of analytical tools for utility lifeline performance and remote sensing for response and recovery.

The challenge to organizations and communities is to build upon the four “Rs” by developing specific metrics to assess the current state of each, and setting precise objectives and actions to improve them.

## Dimensions of Resilience

In addition to the four “Rs,” MCEER’s framework includes four *Dimensions of Resilience*. These can be used to help quantify measures of resilience for various types of physical and organizational systems.

- **Technical** – the ability of physical systems (including all interconnected components) to perform to acceptable/desired levels when subject to disaster;

- **Organizational** – the capacity of organizations - especially those managing critical facilities and disaster-related functions - to make decisions and take actions that contribute to resilience;
- **Social** – consisting of measures specifically designed to lessen the extent to which disaster-stricken communities and governmental jurisdictions suffer negative consequences due to loss of critical services due to disaster; and
- **Economic** – the capacity to reduce both direct and indirect economic losses resulting from disasters.

The performance of Technical and Organizational systems impacts a community’s Social and Economic systems in times of disaster. For example, loss of electrical power (Technical) will negatively impact the way of life of community residents (Social) and businesses (Economic). Thus, resilience objectives for Technical and Organizational dimensions should result in specific tasks that improve performance in each of these dimensions, thereby lessening negative impacts on communities. Likewise, Social and Economic performance measures can be defined as those that improve a community’s ability to withstand and recover rapidly from disaster.

MCEER research, as illustrated in this report, continues to build upon this foundational framework for disaster resilience for earthquakes and other extreme events.



# TOWARDS EARTHQUAKE RESILIENT COMMUNITIES

## *MCEER Research and Outreach Strategy*

MCEER strategically chose to enhance the seismic resilience of communities by focusing on three critical infrastructure systems that need to remain functional following an earthquake: the water distribution network, the power grid, and hospitals. A separate NSF-funded study<sup>1</sup> confirmed that residents of high risk communities rank the availability of water, power, and hospital care following an earthquake as the top three priorities.

Consequently, MCEER develops advanced knowledge and technologies to ensure that these infrastructure systems remain resilient in the aftermath of an earthquake. Integrated engineering tools, decision support systems and related techniques and procedures have been developed to enable decision makers to make more rationally-based investments and allocations of finite resources, and to quantify the expected outcomes in forms that could be communicated to the public and policy makers.

## The Research Program

The research program has concentrated on three major thrust areas that encompass the above scope: electrical power and water delivery systems, health care facilities, and emergency response and recovery. Research on electrical power and water delivery, together with transportation systems, has focused on problems germane to the infrastructural backbone of all communities. Research on health care facilities has targeted issues related to highly complex physical and organizational structures that must provide essential services following earthquakes. Finally, research in emergency response and recovery has concentrated on bringing about improvements in community disaster

response and recovery capacity. The goals and activities of each area are further described in the following paragraphs.

**Development of analytical, experimental and empirical procedures to evaluate and enhance the seismic resilience of lifeline systems.** These studies have included the development of improved models of the post-earthquake restoration processes for electric power and water supply systems; the creation of advanced systems analysis tools to evaluate the joint performance of water supply and electric power networks before and after an earthquake; and a state-of-the-art disaster loss



<sup>1</sup> Perceptions of Earthquake Impacts and Loss Reduction Policy Preferences Among Community Residents and Opinion Leaders," Joanne Nigg, NSF Grant CMS-9812556.





*MCEER's research on health care facilities has focused on complex physical and organizational structures that must be able to provide services following an earthquake.*

modeling procedure that emphasizes understanding how mitigating lifeline infrastructure systems can improve the disaster resilience of a community.

**Seismic response modification technologies to protect structural and nonstructural systems and components in health care facilities from the effects of earthquakes.** The results from these studies are used to provide meaningful input to integrated decision support tools. Research has included the development of new materials and technologies for the seismic retrofit of a wide variety of structures and non-structural components; development of an integrated decision-assisting model to help executives and engineers make informed choices about alternative approaches to improving seismic safety; and formulation and application of an evolutionary theory approach to aseismic design and retrofit, and organizational decision support.

**Development of post-event response and recovery strategies to enhance resilience.** This is achieved by improving the rapidity with which impacts are identified, resources are mobilized and critical systems are restored when earthquakes strike, as well as improving the effectiveness of community recovery strategies that are used following

earthquake disasters. Studies have included the investigation of the relationship between technological and natural disasters; and the development of tools and techniques for loss assessment methodologies and post-earthquake urban damage detection based on remote sensing images.

A "User Network" provides shared access to a wide variety of deliverables, which together with overarching cross-program research activities, supports and further integrates the research areas. Examples of such studies include the development of computational and simulation tools; development of an Internet-based geographic information system management process; and an analysis of economic resilience to earthquakes.

MCEER also engages in cooperative research programs with institutions outside the U.S., including Japan, China, Taiwan, Chile, Italy and others. These international alliances promote global cooperation, collaborative experimental research, and information exchange that advance earthquake engineering and loss mitigation principles in the U.S. and around the world. Many of these activities also serve to provide young U.S. researchers with a broader world view.

## The Education and Outreach Program

MCEER's education program provides learning opportunities for students and educators at the K-12 and university undergraduate and graduate levels, as well as practitioners seeking specialized

training through continuing education. Consistent with NSF's and MCEER's goals, educational activities are designed to stimulate interest in engineering and sciences at the earliest grades, develop future leaders in earthquake engineering and hazards mitigation at the undergraduate and graduate levels, and support today's engineering and emergency management practitioners in efforts to keep pace with changes in their fields.

Outreach includes broad-based dissemination of information and technology through research reports, national and international conferences and workshops, industry partnerships, and a unique national Information Service which provides convenient access to published, recorded and online materials on engineering, geological, social, political and economic aspects of earthquakes and other disasters.

Finally, post-disaster reconnaissance investigations by MCEER researchers offer real-world insights at the cusp of research and education. Though tragic in nature, the devastation wrought by earthquakes and other disasters in the U.S. and abroad serves as a life-size learning laboratory for Center investigators of all disciplines. Quickly dispatched to stricken regions, the teams learn valuable lessons from field investigations and on-site interviews, which often bring new perspectives to the nation's and the Center's research agendas, and contribute to the body of knowledge in earthquake engineering and hazards mitigation.



*Emergency response and recovery research has focused on developing post-event strategies and improving community response following earthquakes.*

# THE TEAM – A PROGRAM AND PROCESS TO ADVANCE RESILIENCE

## *Intellectual and Facilities Infrastructure*

MCEER unites a group of leading researchers from numerous disciplines and institutions throughout the United States to integrate knowledge, expertise, and interdisciplinary perspective with state-of-the-art experimental and computational facilities in earthquake engineering and socioeconomic studies. The result is a systematic “engineered” program of basic and applied research that produces solutions and strategies to reduce the impacts of earthquakes.

## MCEER Leadership

MCEER is led by a team that includes a Director, Deputy Director, Education Director, Diversity Director, and an Executive Committee. Over the years, regular input on Center research and direction was also provided by members of the Scientific Advisory and Implementation Advisory Committees (membership is listed on the inside back cover of this report).

### MCEER Directors

George C. Lee, 1997-2003

Michel Bruneau, 2003-2008

### MCEER Deputy Directors

Tsu Teh Soong, 1997-1998

Michel Bruneau, 1998-2003

Andre Filiatrault, 2003-2007

### MCEER Key Personnel

Makola Abdullah, *Diversity Director*

Thomas L. Anderson, *Strategic Operations Director*

George C. Lee, *Special Tasks Director*

Sabanayagam Thevanayagam, *Education Director*

### MCEER Executive Committee

Thomas O'Rourke, *Cornell University*

Andrei Reinhorn, *University at Buffalo*

Masanobu Shinozuka, *University of California, Irvine*

Kathleen Tierney, *University of Colorado, Boulder*

## MCEER Principal Investigators and Research Areas

Research is carried out by a team of Principal investigators (PIs) that contribute to MCEER deliverables. PI's who participated in the last five years of the NSF-funded project are listed below, grouped by institution. The research area(s) to which they primarily contributed is listed after each name. Senior personnel who have collaborated with the PIs are also listed. Affiliations are current as of May 2008.

### Core Institutions

#### University at Buffalo

Amjad Aref, **2**  
Rajan Batta, **M**  
Michel Bruneau, **0, 2, M**  
Michael Constantinou, **2**  
Gary Dargush, **2, M, U**  
Colin Drury, **M**  
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George Lee, **2, M**  
Gilberto Mosqueda, **2, M**  
Apostolos Papageorgiou, **0, U**  
Andrei Reinhorn, **0, 2, M, U**  
Chris S. Renschler, **M**  
S. Thevanayagam, **E**  
Andrew Whittaker, **2, M, U**

#### Senior Personnel

Ann M. Bisantz, **M**  
Irene Casas, **M**  
Andrea Dargush, **E**  
Daniel Hess, **2, M**  
James Jensen, **3, M**  
Mark Karwan, **M**  
Zach Liang, **2**  
David M. Mark, **M**  
Abani Patra, **M**  
Jin Cheng Qi, **2**  
Pavani Ram, **3, M**

Michael F. Sheridan, **M**  
Sofia Tangelos, **E**  
Mai Tong, **2, M**  
Cornell University  
Rachel Davidson, **0, 1, 3**  
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Masanobu Shinozuka, **0, 1, 3, M, U**

#### University of Colorado, Boulder

Kathleen Tierney, **0, 3**  
Senior Personnel  
Keith Porter, **M**

### Other Institutions

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Rupa Purasinghe, **E**

City University of New York  
Anil Agrawal, **E**

George Mylonakis, **E**  
Florida A&M University  
Makola Abdullah, **E**

#### George Washington University

Ray Williamson, **3**

#### ImageCat, Inc.

Ronald Eguchi, **3, M, U**  
Senior Personnel  
Beverley Adams, **3, M, U**  
Shubharoop Ghosh, **3, M, U**  
Charles Huyck, **3, M, U**

#### MACTEC

Marshall Lew, **2**

#### MLB Company

Henry Jones II, **3**

#### New Jersey Institute of Technology

M. Ala Saadeghvaziri, **1, M**

#### Rensselaer Polytechnic Institute

Ricardo Dobry, **2**

#### Texas Tech University

Senior Personnel  
J. Arn Womble, **3, M**

#### University of British Columbia

Stephanie Chang, **0, 1, 3, U**

#### University of California, Los Angeles

Bijan Houshmand, **3**  
Jonathan Stewart, **M**

#### University of Illinois at Urbana Champaign

Billie F. Spencer, Jr., **E**

#### University of Nevada, Reno

E. Manos Maragakis, **2, U**  
Senior Personnel  
Ahmad Itani, **2**

#### University of Southern California

Tsen-Chung Cheng, **1**  
William Petak, **2, M, U**  
Adam Rose, **0, 1, 3**  
Detlof von Winterfeldt, **2**

#### University of Wisconsin, Green Bay

Daniel Alesch, **2, M, U**  
Senior Personnel  
Lucy Arendt, **2, M**

### Abbreviations:

**0** - Overarching Center-wide Cross Program Research Activities

**1** - Research Thrust on Seismic Evaluation & Retrofit of Lifeline Systems

**2** - Research Thrust on Seismic Retrofit of Acute Care Facilities

**3** - Research Thrust on Emergency Response & Recovery

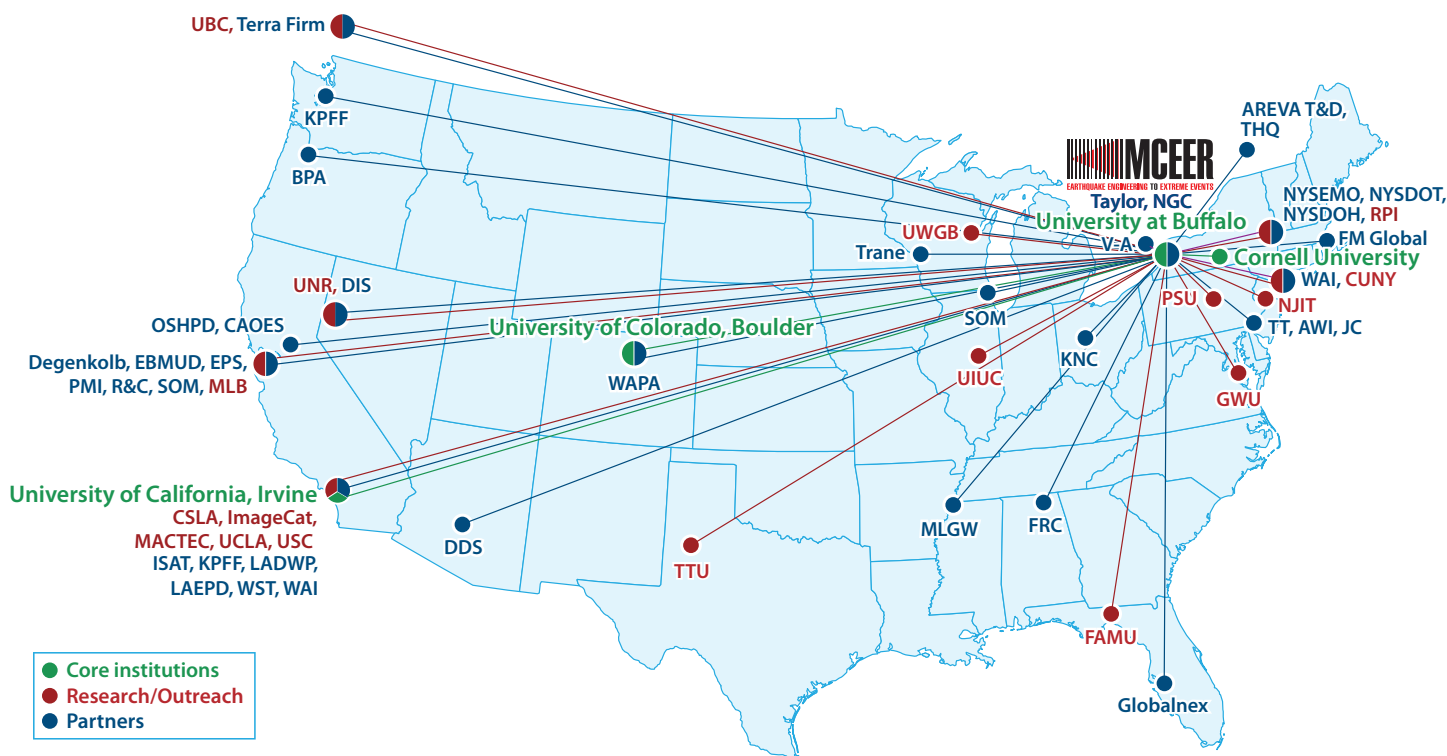
**M** - Mitigation of Infrastructure against Multi-Hazard Extreme Events

**U** - User Networks for Seismic Assessment & Retrofit of Critical Facilities

**E** - Education



# MCEER's Core Institutions, Research & Outreach Participants, and Partners



## KEY

AREVA T&D	JC - Johnson Controls	Taylor - Taylor Devices, Inc.
AWI - Armstrong World Industries, Inc.	KNC - Kinetics Noise Control, Inc.	Terra Firm - Terra Firm Earthquake Preparedness, Inc.
BPA - Bonneville Power Administration	KPFF - KPFF Consulting Engineers, Inc.	THQ - TransEnergie Hydro-Quebec
CSLA - California State University, LA	LADWP - City of Los Angeles Department of Water and Power	Trane
CAOES - California Office of Emergency Services	LAEPD - Los Angeles Emergency Preparedness Department	TT - Thornton Tomasetti Inc.
Cornell University	MACTEC	TTU - Texas Tech University
CUNY - City University of NY	MLB - MLB Company	UBC - University of British Columbia
DDS - Digitexx Data Systems, Corp.	MLGW - Memphis Light Gas and Water Division	UCLA - University of California, Los Angeles
Degenkolb - Degenkolb Engineers	NGC - NGC Testing Services	UIUC - University of Illinois at Urbana, Champaign
DIS - Dynamic Isolation Systems, Inc.	NJIT - New Jersey Institute of Technology	University at Buffalo
EBMUD - East Bay Municipal Utility District	NYSDOH - NYS Department of Health	University of California, Irvine
EPS - Earthquake Protection Systems, Inc.	NYSDOT - NYS Department of Transportation	University of Colorado, Boulder
FAMU - Florida A&M University	NYSEMO - NYS Emergency Management Office	UNR - University of Nevada, Reno
FM Global	OSHPD - California Office of Statewide Health Planning & Development	USC - University of Southern California
FRC - Facility Risk Consultants, Inc.	PMI - Precision Measurement Instruments	UWGB - University of Wisconsin, Green Bay
Globalnex - Globalnex Inc./C.B.I. Europe	PSU - Pennsylvania State University	V-A - Vibro-Acoustics
GWU - George Washington University	R&C - Rutherford & Chekene, Inc.	WAI - Weidlinger Associates, Inc.
ImageCat, Inc.	RPI - Rensselaer Polytechnic Institute	WAPA - Western Area Power Administration
ISAT - ISAT Seismic Bracing	SOM - Skidmore, Owings, & Merrill LLP	WST - WorkSafe Technologies

## Contributors: 1997-2002

Other participants, beyond the list on page 8, who have contributed to early phases of MCEER's NSF-funded project include the following investigators. Note that the affiliations given are the institutions where the MCEER work was conducted; current affiliations (as of May 2008) are listed in parentheses when known.

**Tarek Abdoun**, Rensselaer Polytechnic Institute; **Shahid Ahmad**, University at Buffalo; **Sarah Billington**, Cornell University (now at Stanford University); **Ian Buckle**, University of Nevada, Reno; **Stuart Chen**, University at Buffalo; **Greg Deierlein**, Cornell University (now at Stanford University); **Peter Feenstra**, Cornell University; **Paul Flores**, EQE International; **Patricia Gallagher**, Drexel University; **Howard Hwang**, University of Memphis; **Anthony Ingraffea**, Cornell University; **Daniel Inman**, Virginia Polytechnic Institute; **Richard John**, University of Southern California; **Howard Kunreuther**, University of Pennsylvania; **Babek Mansouri**, University of California, Irvine; **S.T. Mau**, New Jersey Institute of Technology (now at University of Houston); **James McGrath**, Virginia Polytechnic Institute; **James Mitchell**, Virginia Polytechnic Institute; **William A. Mitchell**, Baylor University; **Joanne Nigg**, University of Delaware; **Donald Penn**, Consultant; **Christopher Rojahn**, Applied Technology Council; **Charles Scawthorn**, EQE International (now at Kyoto University); **M.P. Singh**, Virginia Polytechnic Institute; **Tsu Teh Soong**, University at Buffalo; **Ernest Sternberg**, University at Buffalo; **David Tralli**, Consultant; **Gary R. Webb**, University of Delaware (now at University of Oklahoma); **Richard White**, Cornell University.

# THE TEAM – A PROGRAM AND PROCESS TO ADVANCE RESILIENCE

## *Intellectual and Facilities Infrastructure*

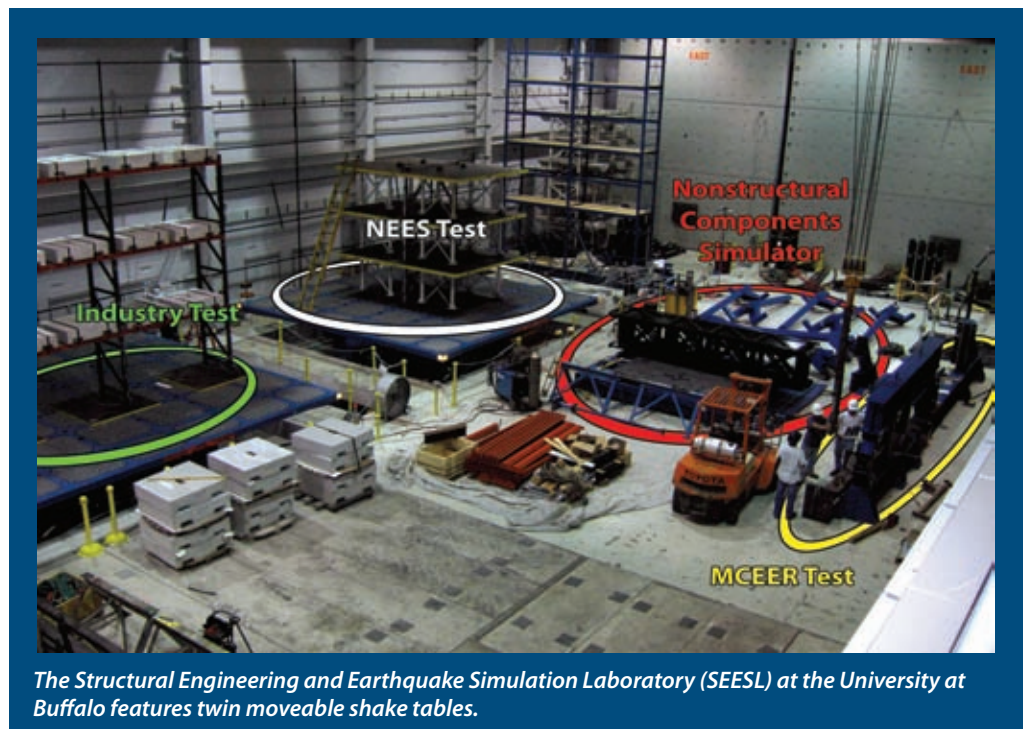
Four key MCEER experimental facilities were significantly expanded as part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program. NEES (<http://www.nees.org>) is a nationwide “collaboratory” that links business, industry, and government agencies with university researchers, students, and state-of-the-art test capabilities via a high-speed Internet network. MCEER affiliated institutions (University at Buffalo, Cornell University, Rensselaer Polytechnic Institute, and the University of Nevada, Reno), have been awarded nearly \$19.5 million from the National Science Foundation, for facility and equipment upgrades. In total, new construction and expansions at these facilities exceeds \$31 million. These facilities, which began operation in 2004, further enhance MCEER’s ability to deliver cutting-edge research on earthquake effects on soils, pipelines, bridges and building structures.

### University at Buffalo

The University at Buffalo’s Structural Engineering and Earthquake Simulation Laboratory (SEESL) added twin six-degrees-of-freedom shake tables as part of its \$10.5 million NSF grant. The new shake tables are capable of seismic testing of structures up to 120 feet in length. The facility also houses two 30-foot high reaction walls, 41 and 23 feet in

length. The \$20 million upgrade makes the facility one of the most versatile in the world.

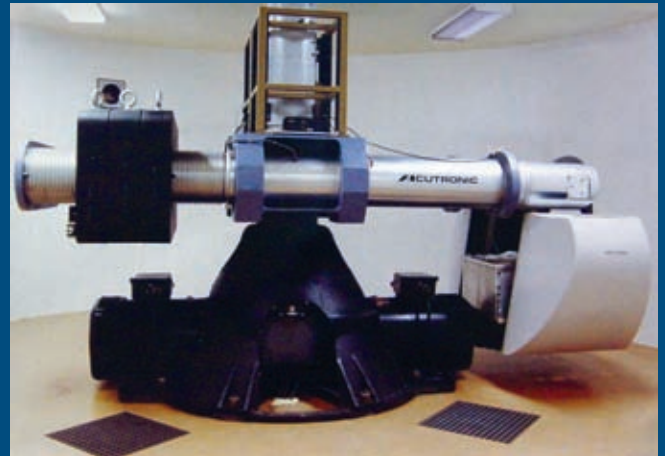
Capabilities were recently expanded by the construction of a Nonstructural Components Simulator (NCS). The NCS is a unique test apparatus that allows researchers to replicate building floor motions on adjacent





## Rensselaer Polytechnic Institute

Rensselaer Polytechnic Institute's (RPI) 100-g ton geotechnical centrifuge underwent a \$2.5 million upgrade. This included the installation of new equipment and software, such as a two-dimensional in-flight earthquake simulator and a four-dimensional in-flight robot, that enable geotechnical engineers to better study the behavior of soils during earthquakes.



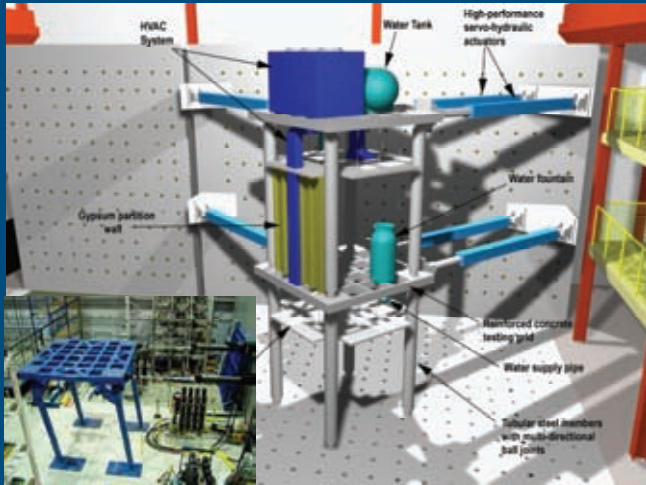
*The Center for Earthquake Engineering Simulation at Rensselaer Polytechnic Institute includes a 100 g-ton centrifuge.*

## University of Nevada, Reno

Two shake tables at the University of Nevada, Reno (UNR) were upgraded, and a third shake table was added as part of the \$4.4 million NSF grant. The three shake tables, each measuring 14 square feet, offer biaxial, or two directional testing of earthquake ground motions on structures. Each table can be operated independently, or in-phase with the other two. The tables can also be moved together to form a single large table. The new and upgraded tables more accurately simulate real earthquakes. Total cost of the expansion and upgrade is \$7 million.



*The James E. Rogers and Louis Weiner, Jr. Bridge Structures Laboratory at the University of Nevada, Reno features three identical shake tables.*



*The University at Buffalo's Nonstructural Components Simulator (UB-NCS) allows testing of a variety of building components and systems.*

building stories to better understand, quantify and control the seismic response of a variety of nonstructural building components. It was developed specifically for performance testing and qualification of building equipment, systems, anchorages, and contents, primarily for vertically distributed nonstructural systems such as piping, venting, and other similar building systems. It also allows the seismic interaction between components to be evaluated.

## Cornell University

A \$2 million NSF grant enabled geotechnical engineers at Cornell University to develop advanced experimental facilities for both full-scale and centrifuge-scale testing, evaluation, and analysis of soil-structure foundation interaction. This capability dramatically enhances the ability to study the impact of earthquakes on buried pipelines and other utilities. The upgrade also included a new 50 foot long and 24 foot high reaction wall.



*The NEES facilities at Cornell University are part of the Bovay Civil Infrastructure Laboratory complex.*





# ENABLING A NEW BREED OF LIFELINES

## *Impacts on Robustness and Rapidity*

**Lifeline systems – water delivery and electric power, as well as others – comprise the infrastructure backbone of all communities. Damage to these systems from earthquakes or other disasters can severely handicap fundamental quality of life and the economic foundations of stricken communities and regions. These impacts can also lead to rippling effects throughout the national and world economies.**

## **Resilient Lifeline Systems**

Electric power generated at power plants is transmitted through a high voltage transmission network to receiving stations and then distributed through lower voltage distribution networks to customers. Water supply networks have similar hierarchical systems consisting of high pressure trunk lines down to distribution pipes to individual customers.

The resilience of these lifeline systems is measured in terms of system robustness or strength, and the rapidity with which services are restored following a disaster. This requires a focus on improving components of the lifeline network's physical infrastructure as well as the organization's ability to implement sound measures in a timely manner to contain potential losses and minimize disruption caused by earthquakes and other extreme events.

MCEER's solution to this problem is the development of a new generation of lifeline systems that are more resilient to earthquakes, and potentially, other disasters. With a specific focus on electric power transmission networks and water delivery systems, MCEER researchers have developed and deployed a Comprehensive Model for Integrated Electric Power Systems and a Comprehensive Model for Integrated Water Supply Systems based on the nation's largest metropolitan area, Los Angeles, California. Both models incorporate modules including fragility and other data from corresponding experimental testing and analyses of the seismic behavior and functionality of various utility system components, and interdependencies between the two systems. The resulting decision support systems have been deployed by the Los Angeles Department of Water and Power (LADWP), where they enhance system-wide planning and engineering.

## **Methodology**

MCEER researchers, together with engineers and management at LADWP for water supply systems, and LADWP and Memphis Light, Gas & Water (MLGW) for electric power networks, have created and deployed predictive models to evaluate lifeline system response and anticipate system performance. The models allow the systems to be "virtually" upgraded and retrofitted and subjected to various probabilistic hazard scenarios. Results help to identify the most effective method of upgrade or retrofit under various hazard conditions.

# COMPREHENSIVE MODEL FOR INTEGRATED ELECTRIC POWER SYSTEMS

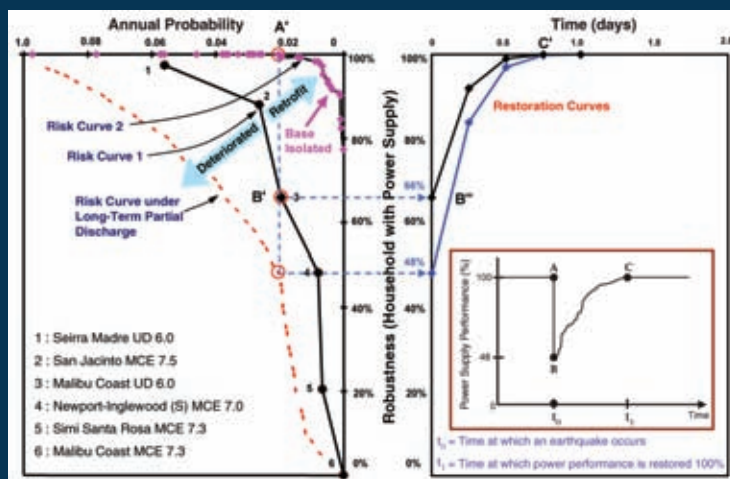
MCEER's Comprehensive Model for Integrated Electric Power Systems provides utilities with the ability to simulate system performance under a variety of hypothetical natural and manmade hazards. This model evaluates system response and predicts system performance. It enables engineers to identify the most effective method of retrofit by "virtually" upgrading the system, and further subjecting it to additional probabilistic hazard scenarios. Retrofit effectiveness is measured in technical, economic and societal dimensions, and more importantly, in terms of the cost/benefit ratio derived for each of different stakeholder groups, thus providing a wide base of decision support criteria.

The model evaluates organizational and socio-economic impacts resulting from damage and disruptions of the power supply. It also considers interactions and interdependencies between electric power and other infrastructure systems serving the same community, particularly the water supply.

Performance prediction is based on power flow analysis (using IPFLOW computer codes from the Electric Power Research Institute) and relevant information collected in GIS format. The model includes regional census tract data and inventory data from the LADWP and MLGW electric transmission systems. It incorporates suites of scenario earthquakes representative of the Los Angeles and Memphis areas.

## MCEER Model Quantifies System Resilience

The MCEER model plots system performance – system robustness and rapidity of restoration – as a function of time. In the graph below, the reduction in performance from 100% at point A (time  $t_0$ ) to 48% at point B represents damage to the system. The restoration curve starting from point B, to the complete recovery point C (back to 100% at time  $t_1$ ), demonstrates the process of restoration. Therefore, B represents a system robustness of 48%, with time for the total restoration ( $t_1 - t_0$ ) representing the rapidity function of resilience. When retrofit strategies are implemented, such as base isolating transformers in Los Angeles to increase their strength by 50% (Risk Curve 1), resilience is enhanced by an increase in robustness from 48% to 66%. When transformer strength is increased by 100% (Risk Curve 2), the annual expected power loss is negligible. This fusion of risk curve and restoration curve represents the process of resilience.



Shinozuka, MCEER-04-SP01 and Technical Report in Preparation



## Study Correlates Reduced Transformer Service Life with Earthquake-induced Internal Component Damage

In a first-ever study of earthquake impacts on electric power transformer functional resilience, MCEER researchers discovered that a loss of prestressing of internal components can lead to transformer failure over time. Researchers found that internal component failure takes place due to: (a) sliding of key spacers, (b) movement or separation of leads, (c) decrease or loss of safe clearance between layers of conductors due to earthquake vibrations, (d) loss of close-fitting tolerances between limbs and yokes, and (e) flexural and rocking of the core frame. Researchers also found that base isolation of transformers reduces the internal demand on components, nearly eliminates sliding of key spacers, and enhances transformer service life following earthquakes.



Saadeghvaziri, MCEER-08-0011

## Impacts of Western Grid Outage Considered for Los Angeles

MCEER's model illustrates the impact of a power disablement in a segment of a 50kV Western grid transmission line in Oregon. The impact cascades through the Western grid, and the Los Angeles system is affected to varying degrees, from partial loss of power to blackout, depending on the location of the disablement. If the incident occurred in a different and less redundant section of the Western grid, a total blackout throughout Los Angeles could result.



Shinozuka, Technical Report in Preparation

## Model Incorporates Fragility Data on Key System Components

Fragility curves of systems, subsystems and equipment damage are incorporated into the MCEER model. Damageability is based on empirical seismic fragility curves for four transmission-critical components at receiving stations: (1) disconnect switches, (2) circuit breakers, (3) transformers and (4) busses. The inventory of network components for LADWP is incorporated from the Western Electricity Coordinating Council's (WECC's) database. MLGW provided the same information for the Memphis system. Other models, including network function restoration, direct and indirect loss estimation methods, and cost of repair and restoration, were also developed to compute resilience and sustainability of power systems.



Shinozuka, Technical Report in Preparation



# COMPREHENSIVE MODEL FOR INTEGRATED WATER SUPPLY SYSTEMS

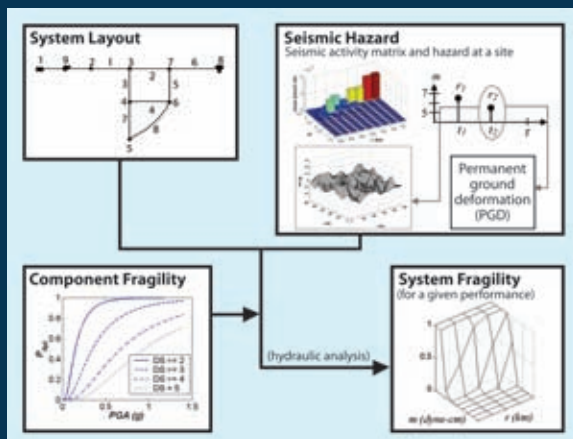
MCEER's Comprehensive Model for Integrated Water Supply Systems supports utility decision making in planning operations, emergency response, and new system facilities and configurations to optimize water supply performance during and after earthquakes. It works with a special program for damaged network flow modeling, known as GIRAFFE (Graphical Iterative Response Analysis for Flow Following Earthquakes), that was developed and validated for the project. The computer model simulates all 11,633 km of water trunk and distribution pipelines and related facilities (e.g., tanks, reservoirs, pressure regulation stations, etc.) in the LADWP system – and it includes specialized software and an ensemble of 59 scenario earthquakes, from which engineers can conduct comprehensive system-wide assessments of earthquake risk.

The system aids in decision support by using risk and reliability assessment tools to provide metrics of system performance. Computer simulations account for the interaction of the water and electric power supplies, and output from the model can be used to evaluate the regional economic and community impacts of water losses. System input and output is visualized through GIS with advanced query logic and web-based features. The simulations are dynamic in time, and can account for loss of service as tanks and local reservoirs lose water over time through leaks and breaks in pipelines.

Most importantly, the system is generic, and the architecture of its computer programs is adaptable to any water supply in the United States. It can also be upgraded to accommodate hazards other than earthquakes, such as floods, landslides, and terrorist attacks. The model and specialized software have been adopted by LADWP as its prime earthquake simulation and planning system.

## Multi-scale Method to Assess Seismic Performance

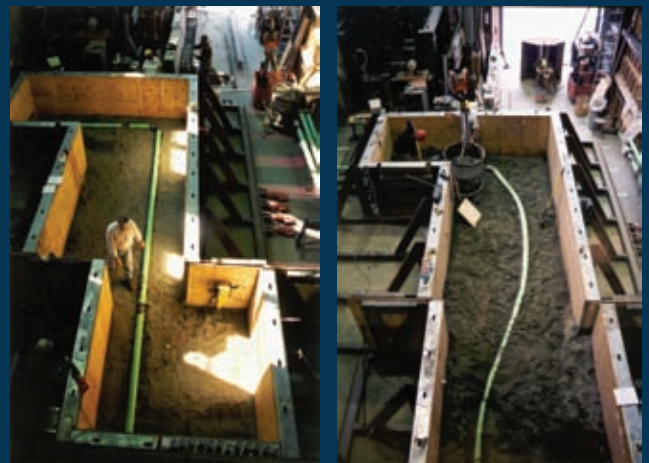
MCEER's model includes capabilities to assess overall seismic performance of water delivery systems by virtually subjecting them to multiple levels of earthquake impacts. This multi-scale methodology produces estimates for seismic fragility, or the probability that a system and/or system component (e.g., pipelines, water tanks, pumps, valves, and reservoirs) will experience specific damage under a seismic event of a given intensity. This capability is part of a decision toolbox that enables users to calculate system seismic fragility, and evaluate and optimize mitigation strategies based on cost-benefit and life-cycle analysis.



Grigoriu, MCEER-08-0009

## Large Scale Experiments Show Impact of Permanent Ground Deformations on Steel Pipelines

MCEER researchers developed and executed the largest laboratory experiments ever performed of ground rupture effects on buried pipelines. The experiments were used to validate an analytical model for evaluating ground rupture effects on pipeline bends, which are critical locations for stress concentration. The analytical model and experimental results were used to make inexpensive changes in welds and wall thickness at the bends that increased capacity by over 100%.

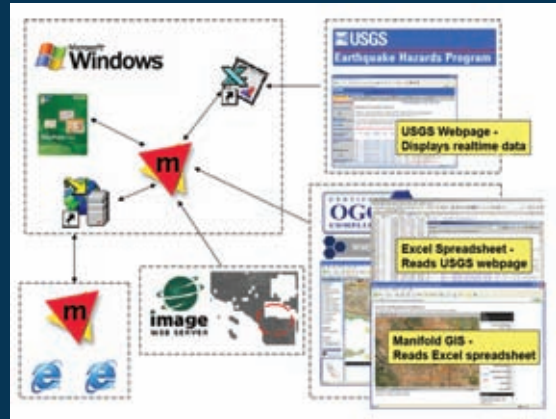


O'Rourke, MCEER-01-SP01



## Advanced IMS Technology Harnessed to Provide Rapid Response

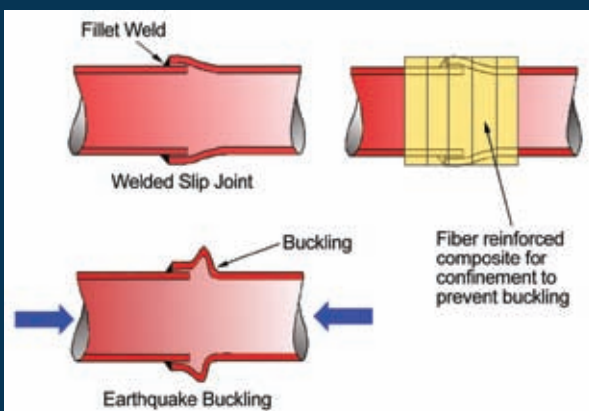
MCEER has pushed the envelope of modern geo-processing for rapid response with advancements in the use of spatial database technology within relational database servers. This fundamentally different approach is based on modern database driven architecture, and exploits the use of SQL (Structured Query Language) and IMS (Internet Map Server) functionality with GIS products, enabling response in near real-time. The integration of this component into the LADWP decision support system has resulted in a fundamental paradigm shift for that organization in its use of GIS to support rapid response.



Lembo, MCEER Bulletin, Vol. 20, No. 2

## Fiber-reinforced Polymer Wraps Add Robustness to Steel Pipelines and Welded Slip Joints

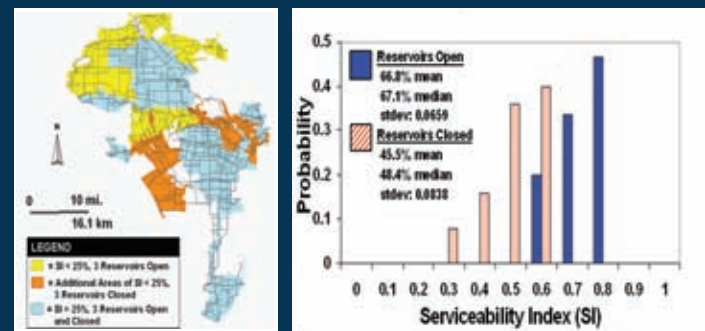
MCEER researchers developed a seismic strengthening system for critical water trunk lines using Fiber Reinforced Polymer (FRP) wrapping to confine and strengthen welded slip joints against seismic compressive forces. Welded slip joints retrofitted with FRP technology restore pipelines to their full strength, as if they were straight sections without joints. This type of reinforcing not only can be used to retrofit existing welded slip joints, but to strengthen new joints during fabrication in the field. The FRPs are now commercially available from several companies.



O'Rourke, MCEER-00-SP01

## Impact of a Repeat Northridge Earthquake on LADWP's Water Supply

A simulation example from GIRAFFE shows the geographic loss of water supply when key reservoirs are open or closed in the LADWP system should a repeat of the Northridge earthquake occur. Results show that the mean serviceability index, defined as the ratio of post- to pre- earthquake water supply, increases by nearly 50% with reservoirs open. This indicates that opening the reservoirs immediately after a serious earthquake is a preferred strategy for emergency response, even though it would require that water purification notices be issued for the entire system.



O'Rourke, MCEER-08-0015 and MCEER-08-0016







# A TRANSFORMATIONAL CONCEPT FOR STRUCTURAL RESILIENCE OF HOSPITALS

*Impacts on Robustness, Redundancy and Rapidity*

Hospitals are among the most complex of engineered facilities – even more complex is the retrofit of existing facilities, many of which have been designed and expanded prior to the development of new knowledge found in today's modern seismic building codes. Because of the substantial investment required to suitably upgrade these facilities, achieving resilience will take place over the course of years, as hospital decision makers consider seismic retrofit needs among other capital expenditures.

## Resilient Hospitals and Acute Care Facilities

The resilience of hospitals is largely measured in terms of robustness, i.e., the strength or ability of the facility to withstand an earthquake without suffering loss of function. Ensuring complete functionality requires that engineering solutions not only address the structural systems, but also the nonstructural components (electrical, mechanical, medical equipment, piping, ceiling systems, buildings contents, etc.).

MCEER's solution to this challenge involves development of seismic retrofit technologies to safeguard hospitals and their nonstructural components, as well as the development of new knowledge and tools that comprise components of integrated decision support systems. These tools and technologies help hospital administrators identify the most appropriate seismic mitigation actions, taking into account structural and nonstructural engineering issues as well as organizational constraints.

## Methodology

MCEER's research has focused on the development of advanced seismic isolation and damping systems (e.g., steel plate shear walls, structural fuses, scissor jack braces, semi-passive damping systems, post-tensioned energy dissipating steel frames, etc.), quantification of fragilities of nonstructural systems, insightful findings on obstacles to implementation of earthquake hazard policies and programs, as well as contributions to advance codes and guidelines.

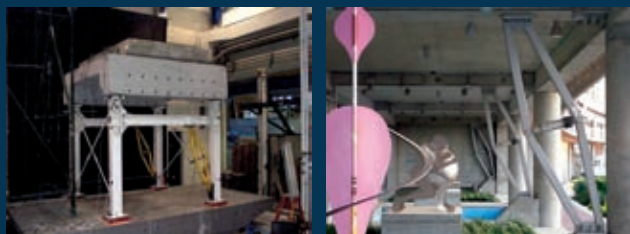
Data from experimental and analytical efforts have been incorporated into two computer-based decision-support technologies: Rehabilitation Decision Analysis Toolbox (RDAT), and Evolutionary Aseismic Design and Retrofit (EADR). These technologies provide engineers and hospital decision makers with tools for analysis of hospital structures and nonstructural systems based on fragility and optimal use of advanced seismic retrofit technologies.

# STRUCTURAL SYSTEMS: RESPONSE MODIFICATION TECHNOLOGIES

MCEER's research program is grounded in the belief that the future of earthquake engineering and loss reduction lies in advanced and emerging technologies. Throughout the years, Center studies have demonstrated technology's ability to make great strides in reducing earthquake hazards while providing a higher level of performance than is possible with conventional techniques. They have also helped pave the way for increased application of a variety of protective systems in new construction and retrofit of buildings, bridges and lifelines around the world. Hospitals provide essential post-disaster functions, and can greatly benefit from the development of technologies that will prevent their closure due to structural or nonstructural damage.

## Protecting Structures with New Seismic Damping Systems

MCEER investigators have developed and patented a scissor-jack bracing concept that leverages the amount of damping that can be imparted at low cost in a structure. The system is a variant of the toggle-brace-damper system, and offers the advantage of a more compact configuration. Experiments demonstrate that despite its small size, the scissor-jack system provides a significant amount of damping while also substantially reducing the seismic response of the tested structure. The device is shown during testing on the shake table (left) and in an actual installation (right).



Constantinou, MCEER-04-0010

## Controlling Seismic Performance Using Metallic Hysteretic Damping and Isolated Floors

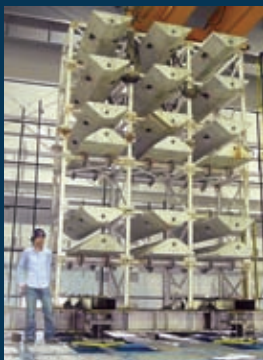
A concept was developed where passive metallic hysteretic damping systems provide significant stiffening and strengthening to decrease drift-related damage, and are combined with floor isolation systems to protect nonstructural components. This helps achieve both structural and nonstructural performance objectives, and system resilience. The Buckling Restrained Braces (BRB) retrofit strategy has been developed into a structural fuse concept, with innovative connection details intended to facilitate replacement of the sacrificial energy dissipating element. Shake table tests of a complete frame with BRBs validated the concept.



Bruneau, MCEER-06-0004 and MCEER-06-0005

## Protecting Nonstructural Components with Seismic Protective Systems

MCEER investigators have developed the exact mathematical characterization, modeling, experimental verification and implementation in computer codes for the triple concave friction pendulum (FP) isolator (an innovative adaptive isolator with potential to significantly impact the application of seismic protective systems). Today, hospitals in California in the design phase use this adaptive seismic isolation system in an effort to reduce isolator displacement demands without impacting the structural and nonstructural system response.

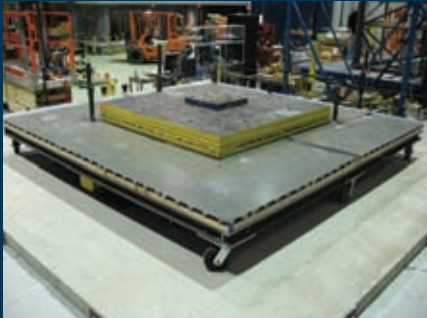


Constantinou, MCEER-08-0007 and MCEER-08-0018



## Floor Isolation Systems for Seismic Applications

Isolated floor systems have been developed and validated using shake table testing for seismic applications. Both direct ground motions and structure floor seismic responses from structural fuse frames were used as inputs. The test results provide knowledge on the performance of the isolated floor systems, and the corresponding acceleration demands on nonstructural components sitting on the isolated floor.



Bruneau, Technical Report in Preparation

## Integrated Design of Acute Care Facilities with Self-Centering Systems

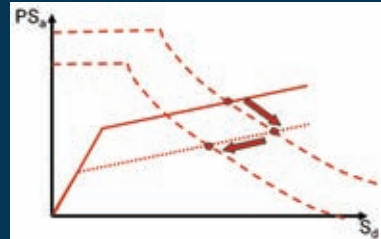
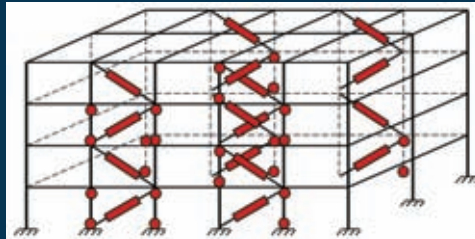
A Post-Tensioned Energy Dissipating (PTED) steel frame concept has been developed as an innovative self-centering system to control the transient and residual response of both structural and nonstructural systems. This system incorporates high strength post-tensioned strands along with sacrificial yielding elements in each beam-to-column connection. It is appealing for hospital buildings, as it has proven effective in reducing floor accelerations for given story displacements.



Filiatrault, MCEER-08-0017

## Increasing Structural Robustness by Weakening and Damping

A strategy has been developed consisting of weakening, and/or softening elements in a structural system while adding passive energy dissipation devices to simultaneously reduce accelerations and deformation response during earthquakes. A two-stage design strategy has been investigated to determine the optimal locations and the amount of weakening and/or softening of structural elements and added damping needed to ensure structural stability. The passive dampers and the weakened elements are designed using an optimization algorithm to obtain a response as close as possible to an actively controlled system. This strategy is incorporated into the IDARC2D computational platform (see *User Network* section).



Reinhorn, MCEER-07-0016



# NONSTRUCTURAL COMPONENTS AND SYSTEMS

Nonstructural components represent 75 percent of the value of typical buildings exposed to earthquakes in the United States. Nonstructural components include all types of building contents, such as mechanical and electrical equipment, architectural components, piping and ceiling systems. MCEER investigators have been studying nonstructural components as part of the Center's hospital research program, because regulations such as California's SB 1953 legislation will require continuous operations of hospital facilities during and after an earthquake by the year 2030. Other building codes, including the 2003 and 2006 International Building Codes, already require certification measures for the installation of nonstructural components systems. These regulations affect as many as 47 states throughout the United States.

In order to better ensure functionality of hospitals and their vital equipment following earthquakes, MCEER investigators have developed experimental protocols to capture fragility data on a variety of these nonstructural systems. Testing has yielded new knowledge on system fragilities, which has been integrated into decision support systems, and incorporated into new designs and installation concepts for a variety of nonstructural components.

## Evaluating and Improving Isolation and Restraint Systems for HVAC Equipment

Experimental research aimed at evaluating the seismic performance of isolation/restraint systems, typical of the systems designed by the MCEER ASHRAE Consortium members (see *Strategic Partnerships*), provides new insight into their use in supporting both light and heavy mechanical equipment. Studies have investigated response amplification due to the engagement of restraint components, sensitivity of seismic performance of the isolation/restraint systems to variations of their restraint component design parameters, and static design capacity of the restraint components to their dynamic (actual) capacity. The test results show that higher amplification of acceleration responses should be expected for light and flexible equipment than for rugged and heavy equipment. An ASHRAE-type isolation/restraint system and an air-handling unit under shake table testing are shown in the figures below.



Filiatrault, MCEER-07-0007 and MCEER-07-0022





## Determining Fragility and Improving Performance of Piping Systems

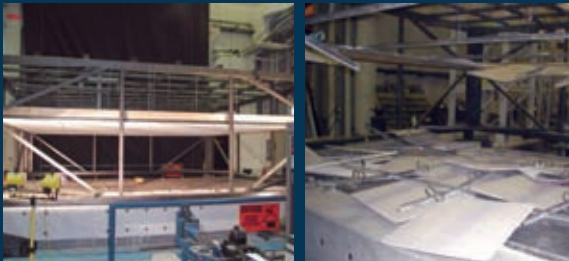
MCEER researchers have experimentally determined seismic fragility of select equipment critical to the post-disaster operation of acute care facilities. Among these are piping and piping subassemblies. Discoveries through shake table tests include poor performance of threaded steel pipes, and the fact that seismic bracing used to limit displacement may actually increase accelerations in piping, causing bracing failures and water leakage. System experiments of the interaction between the pipes and the building's structural systems show that welded steel and copper steel pipes can meet the IBC drift requirement without damage or leakage, while unbraced/braced threaded pipes may not.



Maragakis, MCEER-07-0013

## Improving Performance of Suspended Ceiling Systems

A study of the performance of suspended ceiling systems commonly installed in the U.S. has been carried out. The study evaluated improvements in response offered by the use of retainer clips that secure the ceiling tiles to a suspension system, investigated the effectiveness of including a vertical strut as seismic reinforcement, and evaluated the effect of different boundary conditions on the entire ceiling system during earthquake shaking. Results are reported using damage states and fragility curves, which provide a decision-making tool for performance assessment of suspended ceiling systems. The initial test setup in the UB lab (left) and failure of grid and tiles in one of the test configurations (right) is shown below.



Whittaker, MCEER-06-0001

## Determining Seismic Fragility of Nonstructural Components

The Nonstructural Component Simulator at UB was used to evaluate the seismic performance of a fully equipped emergency room (shown in the photos below) under full-scale floor motions. The experiments included various types of free-standing and anchored medical equipment, piping systems and architectural finishes. Steel-stud partition walls and a suspended ceiling were also included in the experiments to capture, for the first time in a laboratory setting, the interaction and interdependencies between the various types of nonstructural systems in a hospital setting. The experiments illustrated deficiencies in some of the equipment that require improved seismic detailing to keep hospitals operational after an earthquake.



Mosqueda, Filiatrault and Reinhorn, MCEER-08-0026



# INTEGRATION OF STRUCTURAL AND NONSTRUCTURAL SYSTEMS

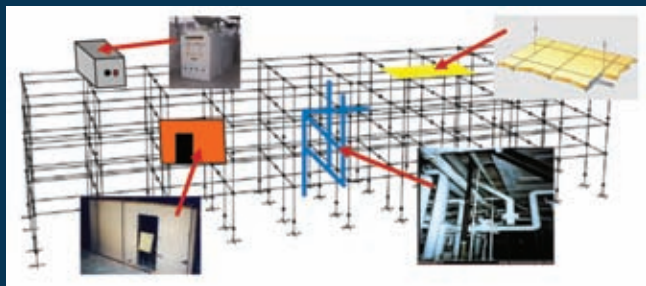
Acute care facilities are extremely complex, and considerable investment may be required to ensure that a facility remains operational following a disaster. The extensive resources that would be required to achieve this level of resilience are not likely available at the onset, and activities to upgrade the facilities may 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 disaster 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 to support such a decision on factual engineering data. MCEER's research investigates how this type of integration could be achieved.

Two decision support platforms were developed: *Rehabilitation Decision Analysis Toolbox* (RDAT) and *Evolutionary Aseismic Design and Retrofit* (EADR). RDAT provides an integration framework based on a fragility approach, while EADR uses an evolutionary analysis procedure that incorporates advanced protective technologies in an uncertain seismic environment, and integrates multiple flexible constraints and rules including non-engineering organizational and socio-economic constraints. Integration of the multiple dimensions of the resilience problem is also investigated from various other perspectives.

## Capturing and Integrating Fragility of Structural and Nonstructural Systems

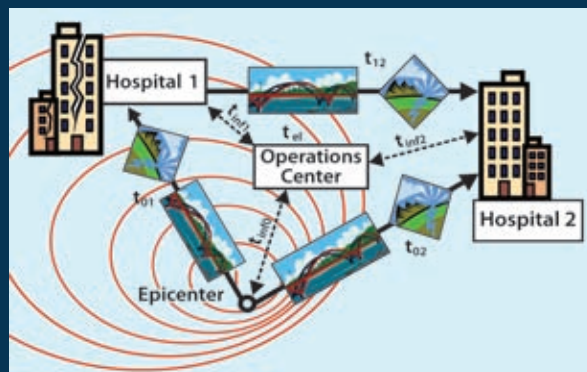
The "MCEER West Coast demonstration hospital" is an acute care facility in California, built to meet the seismic requirements of the 1970 Uniform Building Code. It serves as the testbed to investigate the seismic demands on structural and nonstructural systems and components in acute care facilities, as well as the efficiency of different seismic response modification technologies to reduce the vulnerability of these systems. The testbed incorporated engineering drawings of representative hospitals, provided through partnerships with the California Office of Statewide Health Planning and Development (OSHPD) and the New York State Department of Health.



Grigoriu, MCEER-08-0006

## Technical and Organizational Resilience of Hospitals

An MCEER-developed model enables hospitals to assess organizational resilience together with the impact on operations due to structural and nonstructural damage. Real-time information on post-disaster conditions from regional operations centers is used to determine hospital capacity, optimal transportation routes, and other dynamic factors. The entire approach probabilistically accounts for uncertainties. The procedure is formulated and illustrated for a typical California hospital building as well as for a complex system of hospitals. A resilience model for two hospitals linked by a transportation system is shown in the figure below.

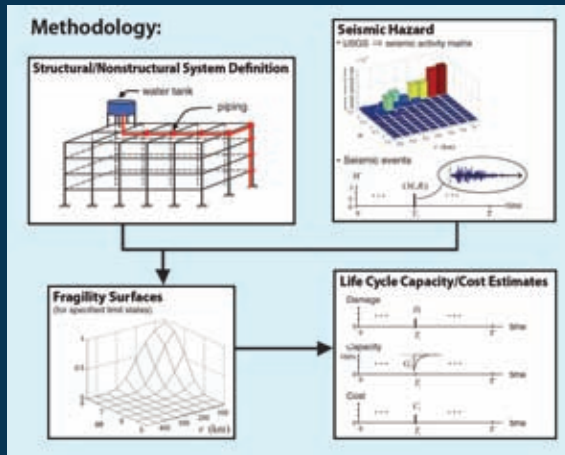


Reinhorn and Bruneau, MCEER-06-0002 and In Preparation



## Computer-Based Decision Support Technologies: RDAT

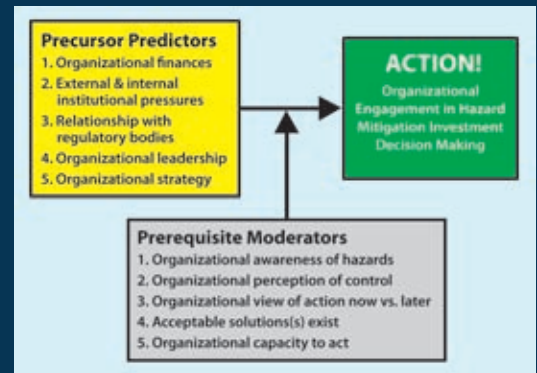
MCEER's *Rehabilitation Decision Analysis Toolbox* (RDAT), built on a user friendly MATLAB interface, is a fragility-based decision support system for evaluating the seismic performance of structural and nonstructural systems in health care facilities under different rehabilitation strategies. The methodology integrates seismic performance analysis and life cycle seismic hazard models with a financial/business model. Development of RDAT involved collaboration by many MCEER researchers and strategic partners, and the integration of significant experimental and analytical data components.



Grigoriu, MCEER-08-0006

## Overcoming Implementation Barriers by Understanding Decision Making

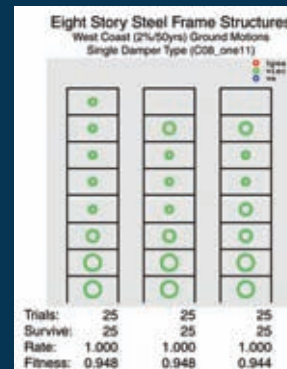
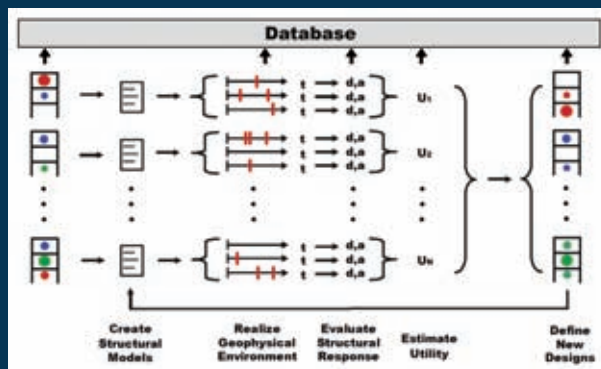
This research provides a comprehensive analysis of the barriers to full implementation of the California legislation (Senate Bill 1953) enacted to enhance the seismic safety of acute care facilities. MCEER researchers have conducted an empirical analysis of how hospital owners make decisions about complying with such regulatory policy. This effort significantly advances the contemporary understanding of how complex organizations make choices about investments in mitigating the likely consequences of extreme events, and instructs hazard safety advocates on effective designs for hazard mitigation policies and programs.



Alesch and Petak, MCEER-08-0014, 07-0002, 05-0006 and 01-0004

## Computer-Based Decision Support Technologies: EADR

The *Evolutionary Aseismic Design and Retrofit* (EADR) decision support software allows users to optimize the size, location and type of damping devices required to provide satisfactory seismic performance in terms of minimizing interstory drift, absolute accelerations of the stories and cost. Performance of nonstructural components can also be explicitly considered. The methodology has been extended to incorporate sociotechnical aspects of the seismic retrofit decision-making process for health care facilities and networks.



Dargush, MCEER-08-0029







# ADVANCING TECHNOLOGIES TO IMPROVE RESPONSE & RECOVERY

## *Impacts on Rapidity, Resourcefulness and Robustness*

Sound response and recovery strategies enable organizations, communities and other social units to return to life as it was prior to the disaster as quickly as possible. Strategies and actions that shorten the time between disaster impact and physical, social, and economic recovery enhance a community's resilience. Such activities must take place quickly following an event. They must also employ limited resources effectively and in ways that contain losses and facilitate optimal recovery. Rapid collection and analysis of data and information is critical to this effort.

## **Resilient Response and Recovery**

MCEER research has developed and validated various sets of tools, techniques, and methodologies for loss estimation, damage assessment, and situation assessment that are capable of supporting a wide range of pre-, trans-, and post-disaster decisions. Over the course of MCEER's history, these tools have been refined and tested against empirical data. They have been used to address significant public policy questions, such as demonstrating that the nation's investment in mitigation programs and projects has been cost effective ( see *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities*, published by the NIBS Multihazard Mitigation Council in 2005). They have also proven to be robust when applied to the study of hazards other than earthquakes.

## **Methodology**

Research has addressed three major topics: (1) new and emerging remote sensing technologies to enhance resilience by producing more accurate building inventories for pre-event loss estimation, and by providing more accurate and timely data for post-event damage detection and situation assessment; (2) advanced loss estimation tools that contribute to resilience by improving response and recovery decision making, including decisions involving post-event restoration of lifelines and community systems; and (3) methods for modeling post-earthquake recovery processes.

Since the terrorist attacks on the World Trade Center complex on September 11, 2001, research has increasingly moved toward the application of MCEER tools and methodologies for hazards other than earthquakes, including the Indian Ocean tsunami, Hurricanes Charley, Ivan, and Katrina, wildfires in California, and other events. These projects are described in more detail in the *Multiple Hazard Design* section.

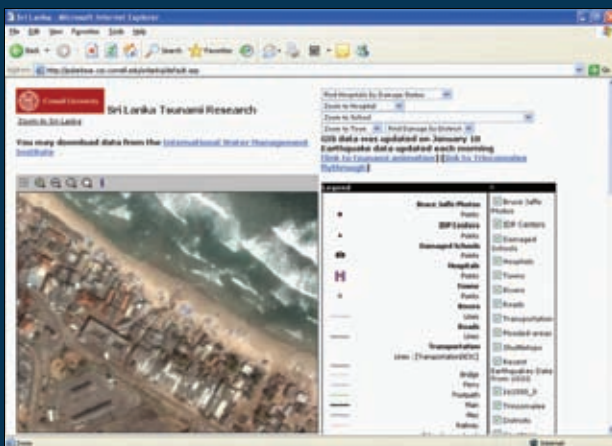
# REMOTE SENSING FOR LOSS ESTIMATION, RESPONSE AND RECOVERY

MCEER's development of remote sensing technologies for loss estimation and rapid damage assessment represent pioneering developments in advancing the speed of response, restoration and recovery following earthquakes and other extreme events. Products developed through this work provide risk managers, planners, and emergency managers with better information on exposed assets, more reliable methodologies to project future earthquake losses, and real-time decision support systems that can facilitate rapid response when earthquakes occur.

The cumulative efforts of MCEER's remote sensing group have brought about breakthrough improvements in post-disaster building damage detection algorithms for earthquake, storm surge, tsunami, flood, and hurricane. The team has developed a HAZUS-compatible remote sensing-based damage scale for hurricanes, along with a radar-based algorithm for flood delineation in urban and rural areas. These algorithms were commercially implemented for the insurance/re-insurance industry, for example following Hurricane Katrina, the 2007 UK floods and the 2008 Mississippi floods.

## Remote Sensing and Web-based GIS

Following initial successes in implementing a database-driven architecture to rapidly and affordably make critical data available to decision-makers after the Niigata earthquakes and the Indian Ocean tsunami, MCEER research on advanced Internet-based map server (IMS) technology has led to the development of GIS products that are immediately available through the Internet following a disaster. This research was carried out in close collaboration with emergency management organizations (LADWP and the Los Angeles Emergency Preparedness Department for earthquake planning, and the New York State Office of Cyber Security and Critical Infrastructure Coordination). The IMS technology enables emergency managers to carry out situation assessment "at a glance," and make rapid decisions regarding deployment of taxed resources following disasters.



Lembo, MCEER Bulletin, Vol. 20, No. 2



## Automated Collapse Detection Tools

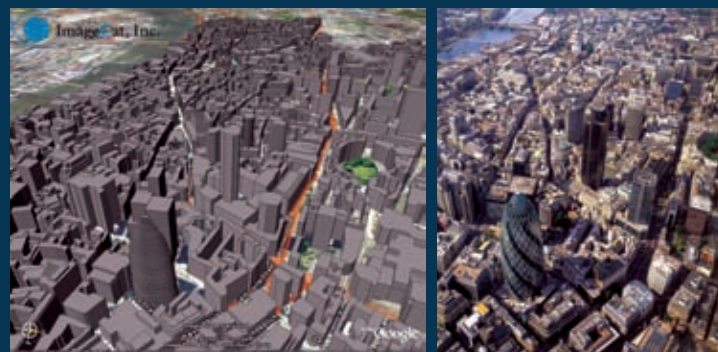
In order to rapidly count the number of collapsed buildings after a disaster, the remote sensing team has devised semi-automated object-oriented processing algorithms that compare spectral and textural characteristics of large sets of individual “objects” (in this case buildings) before and after an extreme event. Results from Bam, Iran following the 2003 earthquake are shown below.



Eguchi, Adams and Huyck, MCEER-08-0020 and MCEER-08-0021

## Remote Sensing Technologies Used to Develop Building Inventories & Estimate Losses

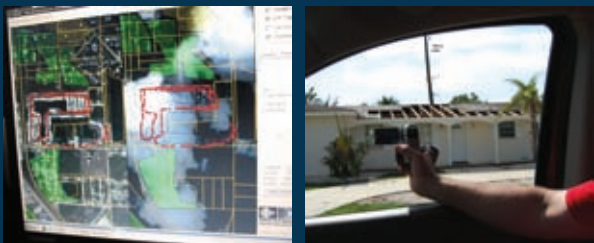
To create building inventories for loss estimation, MCEER researchers have developed an algorithm to quantify square footage, height, and number of stories for individual buildings. Called MIHEA (Mono-Image Height Extraction Algorithm), it provides a means to generate more accurate, up-to-date, and complete inventories on building exposures than are available using conventional methods and data. MIHEA is also useful in generating building inventory data for hard to reach locations, and/or where data is limited or absent. Applications to date include inventory development for major urban areas such as Los Angeles and London (shown below).



Eguchi and Adams, MCEER-08-0022 and MCEER-08-0025

## Post-Earthquake Reconnaissance Tools

The MCEER VIEWS™ (Visualizing the Impacts of Earthquakes with Satellites) platform is a mobile data collection system that integrates GPS-linked video and photographs with base data such as satellite image-derived damage maps, to allow teams to rapidly collect and visualize field data following a disaster. It captures the condition of 1000+ buildings per day (compared to about 20 structures per day for traditional ground surveys) and collects a permanent record of the disaster scene to help facilitate resilient recovery. Satellite imagery first provides an assessment of damage severity and extent on a regional basis, guiding responders to high-priority communities. Individual building damage assessment is then conducted using a combination of high-resolution optical imagery and in-field observations obtained using the VIEWS™ system.



Adams, Eguchi, Ghosh, Huyck and Womble, MCEER-04-SP04, 05-SP01, 08-0024, 08-SP01, 08-SP03 and 08-SP08

## Rapid Situation Assessment in the Aftermath of Damaging Earthquakes

MCEER researchers have used remote sensing technologies to assess damage and recovery in major earthquake disasters, including the Chi-Chi and Marmara earthquakes in 1999, the Bhuj earthquake in 2001, and the Boumerdes and Bam earthquakes in 2003. The figure below shows the distribution of collapsed buildings (red and orange areas) following the Bam earthquake, detected from semi-automated analysis of ‘before’ and ‘after’ optical satellite images.



Adams, MCEER-08-0022



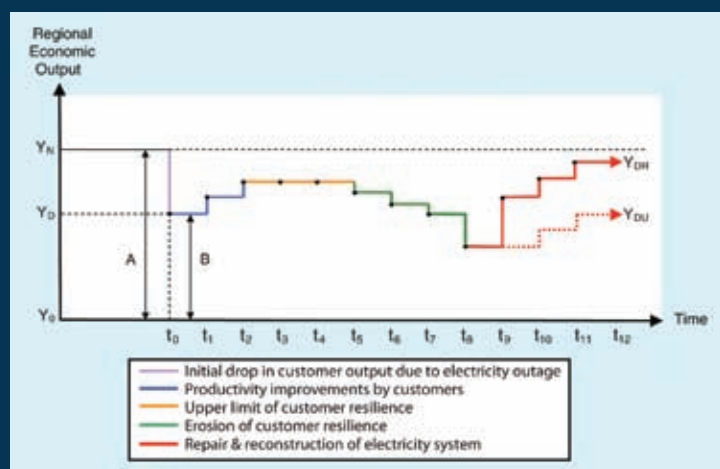
# ENHANCING RESILIENCE BY IMPROVING RAPIDITY AND RESOURCEFULNESS

Post-event response and recovery strategies enhance resilience primarily through improving the rapidity with which impacts are identified, resources are mobilized, and critical systems are restored when earthquakes strike, as well as through improving the effectiveness of community recovery strategies that are used following earthquake disasters. Response and recovery activities enable social units to rapidly return to levels of pre-disaster functioning primarily by enhancing the resourcefulness dimension of resilience—that is, the capacity to effectively mobilize appropriate human and material resources to manage the physical, economic, and social dislocation that earthquakes produce—and also through exploiting and, where necessary, creating system redundancies. Such strategies improve resilience by shortening the time between earthquake impact and physical, social, and economic recovery, while at the same time ensuring that decisions made during the response and recovery period are based on the best available data and information.

While response and recovery activities must be undertaken as rapidly as possible when a major earthquake disaster strikes, it is equally important that the activities that are undertaken are appropriate ones—that is, that they employ resources effectively and in ways that contain losses and facilitate optimal recovery. Thus MCEER's research activities have addressed two inter-related objectives that are of critical importance to society: improving both the speed with which response, restoration, and recovery activities are undertaken, and the quality of the decisions that are made in the immediate and longer-term post-impact period.

## Modeling Individual and Regional Economic Resilience in Computable General Disequilibrium Frameworks

MCEER's research has enhanced the state-of-the-art in modeling the economic impacts of earthquakes and other disasters, including terrorist attacks, in several ways. Disequilibria in relation to shortages of lifeline services and a definition of economic resilience were incorporated into the models. These models, based on a general disequilibrium economic framework, help understand the behavior of individual businesses and households in coping with disasters. They also provide tools for evaluating the benefits of investments in enhancing mitigation and resilience. Additionally, they provide insights into the role of prices and markets in allocating resources in the wake of a disaster and how the structure of a regional economy contributes to its resilience. Static and dynamic resilience in the context of business interruption is shown in the accompanying figure.

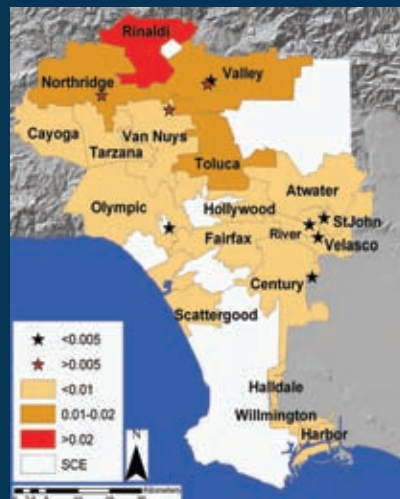


Rose, MCEER-04-SP01 and Technical Report in Preparation



## Restoring Utilities Following an Earthquake

Working with LADWP, MCEER researchers have developed discrete event simulation models of the electric power and water supply restoration processes. The models explicitly represent the key components of the system, the primary restoration team members, and repair materials. Both models represent randomness in the tasks and travel times that are part of a restoration process. The models integrate multiple material and personnel constraints, delays due to damage-related rerouting of repair crews, and many other factors impacting response and recovery. The models also illustrate how resilience can be enhanced through improved decision making. The annual probability of running out of circuit breakers during a post-earthquake restoration, by substation area, is shown in the accompanying figure.



Davidson, MCEER-08-0008

## Community and Organizational Resilience: World Trade Center Disaster Response

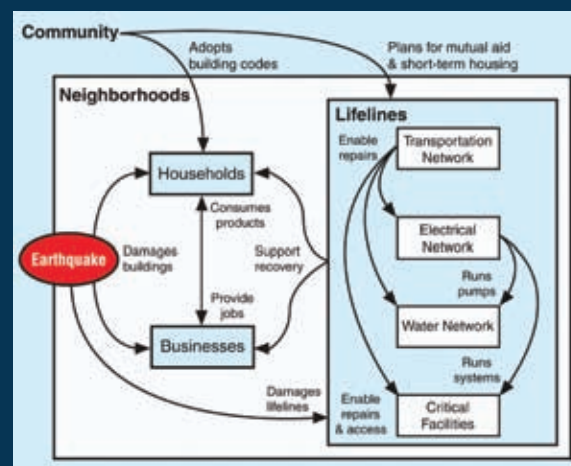
The WTC disaster created major unanticipated problems for responding organizations, including the loss of virtually the entire upper command structure of the Fire Department, the collapse of the building that housed the city's Emergency Operations Center (EOC), and a host of other response-related demands. As a result, responding effectively required extensive improvisation. MCEER researchers developed and documented a typology of multi-organizational responses encompassing many forms of creative, adaptive, and reproductive improvisation. This research resulted in a better understanding of the structure of inter-organizational networks that develop around specific crisis response tasks.



Tierney, MCEER-04-SP01

## Comprehensive Community Recovery Model

The prototype MCEER community recovery model represents the first-ever attempt to model the disaster recovery process comprehensively across various domains (such as housing reconstruction, transportation recovery, restoration of employment) and units of analysis (e.g., households, businesses, or neighborhoods). It also makes it possible for decision makers and recovery planners to see for the first time how activities undertaken in particular domains affect the progress of recovery in other domains and influence the overall recovery process, and how pre- and post-earthquake decisions and policies affect both community vulnerability and community resilience.



Chang, MCEER-07-0014





# ENHANCING RESILIENCE THROUGH ADVANCED NETWORK TOOLS AND INFORMATION TECHNOLOGIES

## *Advancing Resilience in the Marketplace*

Equipping organizations and communities with knowledge, tools and technologies that enable them to stand strong and bounce back when disaster strikes, is fundamental to building earthquake resilient communities. Attaining resilience however, won't happen without the active participation of well-informed and well-equipped practitioner stakeholders who are charged with implementing resilience measures. These practitioners reside within at-risk organizations and communities nationwide.

*While disaster resilience may take root in laboratory experiments or computer analyses, it only takes shape in the world beyond academia when informed, educated and equipped practitioners are empowered through use of the latest knowledge, tools and technologies.*

MCEER's solution is to leverage advanced computer and communication technologies to help tear down geographical barriers and offer speedier methods for distributing and disseminating the latest software tools and hazards-related information. This advanced framework includes MCEER's User Networks, for developing and sharing experimental resources, computational resources and data, through electronic and computerized networks using innovative information technologies. It also includes MCEER User Groups to provide input toward the further development of software and database products. Together, the User Networks and User Groups help to better equip Center investigators and partners in business, industry and government with online connectivity and access to the latest computer tools and databases to advance seismic resilience in communities throughout the U.S. and around the world.

## MCEER's User Networks

MCEER's User Networks ([http://mceer.buffalo.edu/research/User\\_Networks/default.asp](http://mceer.buffalo.edu/research/User_Networks/default.asp)) involve online connectivity of facilities – experimental, computational and educational – in a web centric system using network-wide distributed information prepared by MCEER investigators engaged in a variety of research projects. The network provides a common secured access web portal in which benchmark problems, databases, computational tools, experimental tools, and facilities information are shared. The website is continuously updated to include new information and products of MCEER research. Available tools and databases include:

- Computational tools to evaluate structures and lifelines, including software for fragility and cost evaluation of non-structural systems, water and electrical systems evaluation, and optimal design of response modification technologies.
- Rapid response reports to disseminate field data and on-the-ground observations made by MCEER reconnaissance teams following recent disasters.
- Databases of information for evaluation of structures and lifelines including experimental information on fragility of piping systems, web-based GIS database



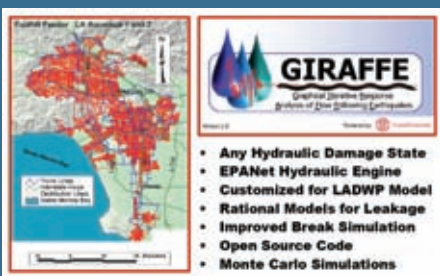
of water distribution systems, databases of case studies of structures, and analytical models for hospital utility systems and subsystems.

- Database of satellite imaging and in-field damage data for interpretation using the VIEWS™ reconnaissance software.
- Information and software to determine direct losses, social impacts, and community resilience.
- Software to evaluate the performance of transportation and water supply systems.

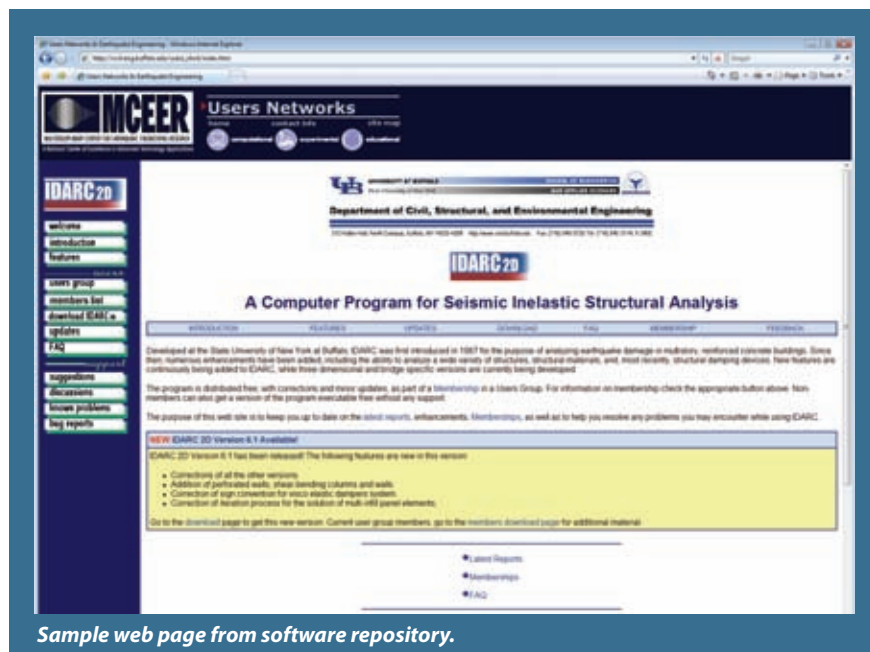
## MCEER User Groups

User Groups consist of researchers, engineers, educators, students and others who share knowledge and worked examples on all aspects of specific software, and provide feedback to the developers to continuously improve software performance and capabilities. Some of these include:

- *Fragility Based Rehabilitation Decision Analysis Toolbox (RDAT) for Acute Care Facilities* software is available with a benchmark problem, sample analysis results and a Matlab tool to simulate the earthquake's temporal distribution, magnitude, and source-to-site distances needed by the software.
- *Evolutionary Aseismic Design and Retrofit (EADR) and Evolutionary Decision Support (EDS) software*, which respectively address design considering resilience and optimization, and integral decision support for socio-economic systems facing earthquake disturbances, or other extreme events.



*GIRAFFE software is inter-operable with the most widely used hydraulic network engine (EPANet), and compatible with the system model used by the Los Angeles Department of Water and Power.*



Sample web page from software repository.

- *GIRAFFE (Graphical Iterative Response Analysis for Flow Following Earthquakes) software* is an open source MCEER product that performs an analysis of damaged hydraulic networks.
- *An online catalog of aerial and satellite images from recent disasters*, and an information portal that provides near real-time information on major disasters (earthquakes, hurricanes, floods, terrorist attacks).

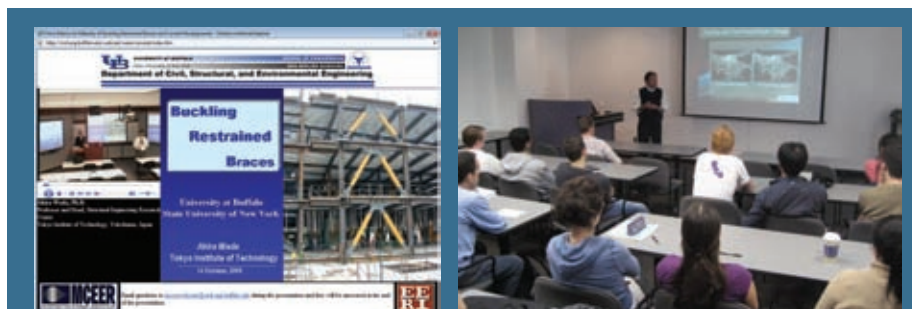
## Software Repository

Computational tools including: (a) software platforms for high performance computing (DIANA, ABAQUS) modified by MCEER investigators to perform fragility/sensitivity analysis and design; (b) advanced software for inelastic analysis and design of structures (IDARC2D, IDARC-Bridge, 3D-BASIS, NSPECTRA, EADR, EADS, RDAT, etc.); (c) procedures for evaluation of fragility (PSHA\_IDARC); and (d) decision tools (RDAT); are down-

loadable from the MCEER website. The nonlinear analysis software platforms include models of advanced damping devices and control, which have been used by various MCEER investigators to develop new design standards for damping systems.

## Webcast Seminars

MCEER, in cooperation with its Student Leadership Council (SLC), the Department of Civil, Structural and Environmental Engineering at the University at Buffalo (UB), and the student chapter of the Earthquake Engineering Research Institute (EERI) at UB jointly sponsor a seminar series on a variety of topics related to earthquake hazard mitigation. Seminars are broadcast live and archived online for later viewing (visit <http://mceer.buffalo.edu/education/webcast/default.asp>). Webcasts by prominent earthquake engineers and social scientists have been streamed to a worldwide audience.



Webcast seminars are broadcast live and archived online for later viewing.

# RESILIENCE THROUGH EDUCATION

## *Advancing Knowledge from K through Gray*

MCEER's education program provides learning opportunities for students and educators at the K-12, undergraduate and graduate university levels, as well as practitioners seeking specialized training through continuing education. Consistent with NSF's and MCEER's goals, educational activities are designed to stimulate interest in engineering and sciences at the earliest grades, develop future leaders in earthquake engineering and hazards mitigation at the undergraduate and graduate levels, and support today's engineering and emergency management practitioners in efforts to keep pace with changes in their fields.

A particular focus of MCEER has been on developing a diverse workforce with a multi-cultural world view. Through its Research Experiences for Undergraduates (REU) Diversity program, college students from groups underrepresented in mathematics, science and engineering have had the opportunity to engage in MCEER research projects, mentored by graduate students and faculty.

International seminars and workshops give undergraduate and graduate students the chance to meet with their peers from other countries, to set the stage for future research collaborations.

## **Pre-College Education & Outreach**

Pre-college education and outreach programs engage students, teachers and home-school parents in Science-Technology-Engineering-Mathematics (STEM) education and specifically earthquake education. Online learning tools (including the comprehensive education resource, *Connecte<sup>2</sup>d Teaching*), reference sources, FAQs and

earthquake exercises are accessible via the MCEER website.

MCEER staff mentor hundreds of students in formal and informal settings. Students receive one-on-one and group instruction and demonstrations, supplemental education in conjunction with school projects and science fairs, and access to an extensive virtual presence.



*Students construct LEGO buildings and test them on an instructional shake table as part of the KiddiEngineering summer program organized by Florida A&M University (left); Third graders built popsicle-stick structures according to seismic design principles and tested them on the UB shake table as part of MCEER's Quake and Shake program (right).*





*MCEER's team placed second at the 2005 Undergraduate Seismic Design Competition (left). MCEER REU student Alma Garcia won EERI's best undergraduate paper award for her paper, Model for Experimental Seismic Fragility Assessment of Nonstructural Systems in Multi-Story Buildings, carried out at UB (right).*

## Undergraduate Education & Outreach

MCEER engages a diverse group of undergraduate students in earthquake engineering research and develops their interest in pursuing advanced studies in this field through a variety of programs. The REU program & REU Diversity program provide undergraduate students with hands-on experience in academic research via 10-week summer internships under the tutelage of MCEER researchers. Over 80% of MCEER's REU students have pursued graduate studies in earthquake engineering.

Undergraduate seismic design competitions encourage graduate studies in earthquake engineering by introducing undergraduates to earthquake resistant design and construction of structures using advanced earthquake protective systems. Over 65 undergraduate students from MCEER-affiliated institutions have participated in the competitions, often held in conjunction with the other earthquake engineering centers.

Programs for underrepresented students involving three minority-serving institutions, California State University Los Angeles, City College of New York, and Florida A&M University, help to promote earthquake engineering to underrepresented students (African American, Hispanic and females). Formal and informal education projects include seismic analyses of buildings using three-dimensional computer models

and mini-shake tables for seismic testing. Presentations, laboratory tours, and internship and fellowship programs are part of a coordinated effort to provide underrepresented students with earthquake engineering education opportunities that would not otherwise be possible.

## Graduate Education & Outreach

MCEER has successfully developed programs to educate future leaders with diverse talents, interdisciplinary experience and leadership skills. The Student Leadership Council (SLC) encourages students at participating institutions to interact, network, develop collaborative projects, and participate in international conferences, post-earthquake reconnaissance programs, Tri-Center Field Missions, annual meetings and workshops/seminars (see *User Networks*). It provides a mechanism to engage students and develop their leadership

skills, many of whom are applying their MCEER-acquired knowledge today in academia, professional practice and government agencies. With an annual membership of approximately 40 students, SLC members actively participate in research that addresses all disciplinary specialties within earthquake hazard mitigation.

Comments and feedback from industry indicate that students exposed to MCEER's program have been educated to readily understand and acknowledge that emergency preparedness and management projects are multidisciplinary in nature. They are more adept at bridging work by academia, private sector, researchers, and specialized research centers, and have a better understanding of the broader picture/total perspective, from science to policy.

Web-based virtual experiments offer instruction through animated presentations that describe earthquakes, earthquake engineering, and earthquake engineering research. These tools, developed using MCEER research, mimic the effects of structural control and base isolation systems on multi-story buildings and structural dynamic experiments. They help to provide a conceptual understanding of structural behavior under seismic loading, and augment teaching structural dynamics and earthquake engineering analysis at institutions that do not have facilities to conduct dynamic experiments.



*The 2007 Tri-Center Field Mission to Japan included a visit to E-Defense (left) and SLC members present their research to industry partners and researchers at MCEER's annual meetings (right).*

# RESILIENCE THROUGH OUTREACH

## *Advancing Knowledge through Dissemination*

MCEER outreach efforts include broad-based dissemination of information and technology through research reports, national and international conferences and workshops, industry partnerships, and a national Information Service that provides convenient access to published, recorded and on-line materials on engineering, geological, social, political, and economic aspects of earthquakes.

### Information Service

MCEER's Information Service is a comprehensive source for earthquake engineering and loss reduction information, providing reference services including literature searches and document delivery to academics, practitioners, policymakers and at-large publics worldwide. Information professionals on staff fulfill an average of 200 requests each week.



*Quakeline® provides easy access to thousands of records on literature related to earthquake engineering.*

QUAKELINE® is a unique, publicly-accessible bibliographic database featuring distinctive materials that cover the field of earthquake engineering. Updated monthly and also available online, QUAKELINE® provides easy access to tens of thousands of records on books, journals, technical reports and other earthquake engineering and natural hazards mitigation literature.

### Publications

MCEER publications foster knowledge and technology transfer by communicating the latest developments in earthquake engineering research and loss reduction practices to academic researchers, consultants, practitioners and policymakers in government and the private sector.

Since its inception, the Center has published more than 500 technical reports, workshop and conference proceedings,

special publications and monographs.

Reports are offered in a variety of formats (print, CD, online, multi-media, etc.) and are peer-reviewed. Over 20,000 reports have been distributed worldwide to over 8,000 individuals and organizations between 1997 and 2007, and are available from the Library of Congress and the National Technical Information Service. In addition, the *MCEER Bulletin* newsletter, offered in both print and electronic format, reaches over 7,000 subscribers world-wide.

### Website

MCEER's website (<http://mceer.buffalo.edu>) reflects its position as a leading provider of earthquake hazard mitigation materials. The website supports the mission, goals, research, partnerships, education, publications, outreach efforts and activities of MCEER and draws a wide range of visitors, including academics, practicing engineers and industry professionals, public policy makers, students, teachers, and the general public. On average, over 4,500 people view more than 10,000 pages each week. Popular destinations include Center



*MCEER publications, including technical reports, workshop and conference proceedings, special publications and a newsletter, describe the latest research and developments in the field of disaster mitigation.*



research pages, reconnaissance reports, Bulletin articles, and the MCEER Information Service's daily compilations of resources on current disasters.

The website is also used as a medium to share breaking news and discoveries following disasters. For example, within days following Hurricane Katrina, findings from MCEER's reconnaissance team were available from the website. Images and GPS coordinates obtained from the VIEWS™ system were integrated with Google Earth, and provided as part of the team's preliminary damage reports. A few months later, a seminar given by the team was webcast and archived on the site, along with a series of full length reports.



The MCEER website is a comprehensive source for information on earthquake engineering, hazards mitigation, disaster preparedness, and related topics.

## Impact on Practice, Design Codes & Codes of Practice

MCEER investigators energize the transfer of new knowledge, tools and technologies by contributing to advancements in codes and guidelines. These efforts provide structural engineers with new procedures for the analysis and evaluation of existing structures, and design of seismic retrofit strategies, as well as robust procedures for the analysis and design of passive energy dissipation systems, an area of particular expertise at MCEER.

In some instances, MCEER has led in the development of next generation design standards for practicing engineers. Two recent examples include the *Seismic Retrofitting Manual for Highway Structures: Part 1 – Bridges and Part 2 – Retaining Structures, Slopes, Tunnels, Culverts and Roadways*, [http://mceer.buffalo.edu/publications/Bridge\\_and\\_Highway\\_Reports/Bridge\\_Manuals.asp](http://mceer.buffalo.edu/publications/Bridge_and_Highway_Reports/Bridge_Manuals.asp),

developed through a project funded by the Federal Highway Administration (FHWA) and *Recommended LRFD Guidelines for the Seismic Design of Highway Bridges*, <http://mceer.buffalo.edu/publications/Codes/03-SP03/default.asp>, produced in partnership with the Applied Technology Council (ATC) with funding from the National Cooperative Highway Research Program (NCHRP).

Notable contributions by MCEER investigators within the scope of the NSF-funded project (1997-2007) include the development of *Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components* (2007). This document, produced in collaboration with ATC, Mid-America Earthquake Center and Pacific Earthquake Engineering Research Center, presents an overview of the next-generation of performance-based seismic design procedures, and discussions on a variety of topics and issues germane to these protocols (<http://www.atccouncil.org/pdfs/FEMA461.pdf>).

MCEER researchers made key contributions to the development of the technical basis (Technical Report MCEER-00-0010) for the two most advanced codes and guidelines related to the implementation of passive energy dissipation systems. *FEMA 273/274 Guidelines for the Seismic Rehabilitation of Buildings* (1998) provides structural engineers with new information on procedures for the analysis and evaluation of existing structures, and design of seismic retrofit strategies; and the *NEHRP Guidelines for Seismic Regulations for New Buildings and Other Structures*, 2000 and 2003 editions, introduces robust procedures for the analysis and design of passive energy dissipation systems (Appendix to Chapter 13) using force-based methods of analysis that are consistent with methods used for the analysis and design of conventional construction.

In another effort, investigators co-authored the American Institute of Steel Construction's *Design Guide 20/Steel Plate Shear Walls*, (2007). The document incorporates MCEER's work on steel plate shear walls (<http://www.aisc.org>).

## Workshops & Conferences

MCEER has organized and/or sponsored a number of workshops and conferences to present research results as well as to gather experts together to discuss ideas and formulate future research agendas. Over 35 events have been held between 1997 and 2007, involving thousands of participants.

For example, MCEER hosted the *Symposium on Seismic Regulations and Challenges for Protecting Building Equipment, Components, and Operations*, held at the University at Buffalo in October 2007. Focusing on current real-world non-structural challenges, several of MCEER's industry/practitioner partners shared their insights, expertise, and challenges faced in meeting more stringent requirements for qualified installation of building electrical, mechanical and medical equipment (see *Strategic Partnerships*).

In another event, MCEER teamed with the Architectural Engineering Institute (AEI) of ASCE to convene over 100 structural engineers, architects, faculty researchers, and students in New York City for the *Symposium on Emerging Developments in Multi-Hazard Engineering* in September 2007. The event featured presentations by nationally-recognized researchers and practitioners that highlighted recent advances in the emerging field of multiple hazard engineering.



MCEER Partner Christos Tokas, California Office of Statewide Health Planning and Development, discussed safety requirements for nonstructural components in health care facilities following earthquakes at a recent MCEER symposium.

Armstrong

Degenkolb

DIGIT<sup>3</sup>EXX

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# RESILIENCE THROUGH STRATEGIC PARTNERSHIPS

## Advancing Practices With and Through Business, Industry & Government

MCEER partnerships with business, industry and government focus on mutual interest and benefits, both to long-term Center goals and near-term member interests. More than 50 such organizations participate in MCEER research, education and outreach programs. These include protective technology manufacturers and suppliers, building equipment manufacturers, leading structural engineering firms, specialty contractors, government regulatory and service agencies, major municipal and regional electric power and water utilities, state and local emergency management offices, and other end users of Center-developed solutions.

Exchanges between Center researchers and strategic partners help drive MCEER's research program, develop the next generation of earthquake engineers and hazards practitioners, and bring about resilience solutions to real-world problems posed by earthquakes and other extreme events.

## Strategic Partnerships for Mutual Gain

Business, industry and government partners interact with MCEER through a variety of channels.

**MCEER's Strategic Partnerships Network** is an annual membership-based program that forges strategic alliances with business, industry and government partners. Network alliances collectively enhance research, development, understanding and application of advanced technologies to enhance disaster resilience. Members receive a variety of benefits including close interaction with Center researchers and students, seats on MCEER's Industry Advisory Board with opportunities to influence research strategy, early access to new knowledge, tools and technologies developed through MCEER research, and networking opportunities with other members.

**MCEER Industry Consortia** contribute toward targeted research that advances the Center's mission while simultaneously answering pressing industry concerns. For example, the Electric Utility Consortium (EUC) is a collaboration with the Electric Power Research Institute (EPRI) and participating electric power equipment manufacturers. The EUC was created in response to the needs of electrical utilities and focuses specifically on the seismic behavior of electrical



Filiatrault, MCEER-07-0007 and 07-0022

MCEER's Electric Utility Consortium and ASHRAE Consortium team Center researchers with technical committees of industry professionals to solve problems associated with electric power substations (top) and HVAC equipment (bottom).





*More than 100 people, principally from industry, attended an MCEER-organized symposium and demonstration test of a fully-equipped composite hospital room.*

substation equipment. Another consortium is a collaboration with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). This consortium studies the performance of restraint and isolation systems for protection of equipment and other nonstructural components typically found in hospitals and other critical facilities.

**MCEER Industry Advisory Board (IAB)** comprises 56 members representing 35 organizations and firms. These include both private-sector members of the Center's Strategic Partnerships Network and strategically-related government agencies. This balance of public-private sector participation helps ensure that MCEER solutions meet the needs of practitioners and end users, as well as the requirements of government regulators.

The IAB helps direct Center research, education and outreach programs by actively contributing insight and practitioner perspectives, providing important test-beds for the development of new technologies, engaging researchers and graduate students in real-world issues, and helping to advance the state-of-the-art and state-of-practice in earthquake engineering and disaster resilience by ushering new knowledge, tools and technologies into practice.

*"In just a scant nine years, MCEER has literally changed the way the engineering profession addresses seismic protection, and has developed the tools needed to define and achieve structural resilience."*

– Douglas Taylor, President, Taylor Devices, Inc.

## Protecting Nonstructural Components

Industry practitioners and university-based researchers gathered together for the dedication of the UB Nonstructural Components Simulator. Activities included a demonstration test of a composite hospital room, fully stocked with emergency and other medical equipment, including sprinkler and medical gas piping. The dedication was preceded by a *Symposium on Seismic Regulations and Challenges for Protecting Building Equipment, Components, and Operations* (See *Outreach*). Focusing on current real-world nonstructural challenges, the Symposium featured speakers from among MCEER industry/practitioner partners. MCEER's research in protection of nonstructural components is unparalleled, and is enthusiastically championed by IAB members as an area of continued real-world needs and research opportunity for the Center over the next two decades.

*"MCEER research into innovative seismic resisting systems is finding wide application in California Hospitals."*

– Christos Tokas, Manager, California Hospital Seismic Retrofit Program, Office of Statewide Health Planning and Development

## Developing New Products

Toggle and scissor-jack braces are among new product lines of MCEER partner Taylor Devices, Inc., as a result of the company's collaborations with MCEER. The scissor-jack brace, patented by the Research Foundation of the State University of New York, University at Buffalo, has seen application

*The scissor jack brace protective system was developed by MCEER researchers in collaboration with members of its Strategic Partnerships Network.*

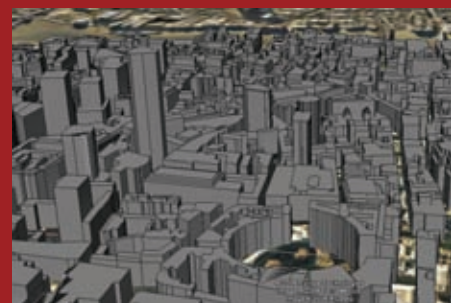


Constantinou, MCEER-04-0010

(July 2006) in the Olympic Committee Building in Cyprus (see *Hospitals*). Among other applications, toggle braces were included in the construction of the Yerba Buena Tower in San Francisco.

## Collaborating Worldwide

MCEER researchers have substantial collaborations with agencies around the world that provide images and other data to advance development of remote sensing technologies. These include the European Space Agency; NIK Insaat Tikaret (Turkey); AirborneL, which provided LIDAR data for Los Angeles; Japan's Earthquake Disaster Mitigation Research Center (EDM), which has provided satellite imagery for the 1994 Northridge earthquake and IKONOS satellite coverage for the Bhuj earthquake; the National Center for Research on Earthquake Engineering in Taiwan, which provided IKONOS image data from the 1999 Taiwan earthquake; USGS, which has provided Landsat 7 coverage for Los Angeles; NOAA, provider of LIDAR data for Southern California; and European and Canadian radar satellite data providers following the 1997 UK floods. In that last-mentioned event, MCEER accurately delineated flood boundaries, enabling the re-insurance industry to assess losses.



Eguchi and Adams, MCEER-08-0020 and 08-0022

*Satellite images like that of London (left) enable MCEER remote sensing researchers to use MIHEA software to develop the 3-D rendering on the right.*

# INTERNATIONAL COLLABORATIVE RESEARCH

## *Engaging Experts from Around the World*

MCEER has a distinguished and rewarding history of international cooperation, which began with its inception as the National Center for Earthquake Engineering Research (NCEER) in 1986. At that time, NCEER was the only NSF established earthquake engineering research center in the United States. It served as the focal point for international earthquake engineering activities featuring workshops, joint research projects, scholarly exchanges, student exchanges and center-to-center collaborations. These activities continue to flourish and expand under MCEER.

Today, MCEER has cooperative projects and programs with numerous countries around the world where earthquake resistant design of buildings and infrastructure systems is a concern. This success is no doubt the result of the “center approach” in earthquake engineering pioneered by NSF, where multidisciplinary experts from multiple institutions work together to address large-scale problems in a systems-integrated fashion. MCEER not only engages various U.S. experts, but also those from international centers in Japan, China, Korea, Taiwan, Turkey, Italy, Canada, Mexico, and organized research units in other countries, over the full range of MCEER research and education activities.

## International Collaborations & Exchanges

MCEER has carried out dozens of international workshops, particularly in China, Japan, Taiwan, Korea, Italy and the United Kingdom in addition to the U.S. For example, since 2003, leading experts in the field of remote sensing technologies have gathered for a series of annual international workshops to discuss potential applications for improved disaster response. Workshops have been held in Irvine, California (2003), Newport Beach, California (2004), Chiba, Japan (2005), Cambridge, UK (2006), Washington, DC (2007) and Pavia, Italy (2008).

MCEER is also a member of a unique professional consortium called the Asian-Pacific Network of Centers for Earthquake Engineering Research (ANCER). ANCER was established in 2001 to enhance research, education and technology transfer activities involving a network of centers located throughout the world. Annual meetings have been held in China, Korea and the U.S.

U.S.-Japan research on earthquake resistant design of lifeline facilities focuses on the earthquake per-

formance of lifelines, with emphasis on liquefaction-induced large ground deformations. The research program has developed case histories of earthquake-induced ground deformations and their effects on lifeline facilities in the U.S. and Japan, resulting in the publication of a two-volume report (NCEER-92-0001 and NCEER-92-0002). In addition, the proceedings from eight joint workshops published by MCEER/NCEER between 1989-2003 cover case history data, analytical modeling, experimental studies and recommendations for improved practices.



Adams, MCEER-05-SP03

*The international workshop series on remote sensing offers an opportunity for experts from around the world to discuss applications for improved disaster response.*





## Research Projects

MCEER and the National Center for Research on Earthquake Engineering (NCREE) in Taiwan have had a cooperative research agreement since 1995. A large number of collaborative experiments have been conducted over the past decade, some based on observations and data collected following the 1999 Chi-Chi earthquake. For example, an experimental research project has been carried out to investigate the performance of full-scale Steel Plate Shear Walls (SPSW) for seismic design and retrofit of building structures. The project led to discoveries on the behavior of SPSWs with direct implications for design requirements.

In another project, MCEER, NCREE and Bridgestone Corporation (Tokyo, Japan) collaborated to protect transformer/bushing systems using base isolation. The research includes design of new base isolation systems, 3D shake table tests, analytical modeling of the isolator and numerical simulation of its seismic performance, and development of a simplified procedure for isolator design.

This fruitful collaboration also extends to the work funded by other sponsors (such as FHWA) to investigate the performance of new types of seismic isolators, and new concepts for seismic-resistant precast segmental post-tensioned concrete bridge columns.

## Reconnaissance Missions

In the past decade, MCEER teams have conducted post-earthquake and multi-hazard reconnaissance investigations throughout the world. Quickly dispatched to stricken regions, MCEER researchers learn valuable lessons from field investigations and on-site interviews, which often bring new perspectives to both the nation's and the Center's research agendas. Post-investigation technical briefings and reports contribute to the worldwide body of knowledge in earthquake engineering and hazards mitigation. Notable field missions include the 1999



Bruneau, MCEER-08-0010 and MCEER-08-0012

Marmara, Turkey, 1999 Chi-Chi, Taiwan, 2003 Boumerdes, Algeria, 2003 Bam, Iran, 2007 Pisco, Peru and 2008 Wenchuan, China earthquakes; 2001 World Trade Center terrorist attack in New York City; 2004 Charley and 2005 Katrina hurricanes; 2004 tsunami/earthquake disaster in South Asia; 2007 California wildfires; and 2008 tornado outbreak, Mid-Southern U.S.

## National Benefits

MCEER has served the U.S. earthquake engineering community by providing linkages and collaborations with a large number of countries interested in earthquake mitigation and response. Many technology transfer activities have taken place between the U.S. and these countries. At the same time, these collaborations have enhanced the opportunity of many U.S. institutions to educate high quality international graduate students who can function in a globally-connected, innovation-driven world



Feng, MCEER-05-0008

*MCEER and NCREE carried out a number of research projects, including an experimental program on steel plate shear walls for seismic design and retrofit (left) and the development of a new base isolation system for transformer/bushing systems (above).*

where engineering crosses national borders. These technology transfer and international educational programs help to ensure the leadership position and reputation of the U.S. in the global earthquake engineering community. Finally, the U.S. also benefits from the knowledge developed in these countries to help establish earthquake resilient communities throughout the world.



*MCEER's SLC members participated in an international design competition held in Taiwan. Participation in these multi-national events helps to foster the development of globally-connected young professionals.*



*MCEER researchers learn valuable lessons from field investigations and on-site interviews following disasters, which often bring new perspectives to the nation's and the Center's research agendas.*



# RECOGNITIONS & ACHIEVEMENTS

## MCEER Celebrates Excellence

Many MCEER team members have been honored by the scientific community with national awards and recognitions for their National Science Foundation-funded MCEER work. Selected National Science Foundation (NSF), American Society of Civil Engineers (ASCE) and Earthquake Engineering Research Institute (EERI) awards and recognitions given to investigators and students are included here, as is congressional testimony delivered by MCEER investigators relevant to earthquake hazard mitigation activities. A complete list of honors and awards is available by visiting: <http://mceer.buffalo.edu/outreach/people/default.asp>.

### Presidential Honors

**George C. Lee**, Professor, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, received the 2006 *Presidential Award for Excellence in Science, Mathematics and Engineering Mentoring* from President George W. Bush in a ceremony at the White House in November 2007. The annual award, administered by the National Science Foundation, recognizes commitment to mentoring students and improving the participation of minorities, women and disabled students in science, mathematics and engineering.

### National Science Foundation Awards

**Gilberto Mosqueda**, Assistant Professor, Department of Civil, Structural and Environmental Engineering, University at Buffalo, received NSF's Faculty Early Career Development (CAREER) Award in 2008.

### Congressional Testimony

**Adam Z. Rose**, Professor, University of Southern California, presented "Future Savings from Mitigation Activities 2003-2005" and "Benefits of Advanced Seismic Monitoring" before the Congressional Hazards Alliance States Caucus in February 2006.

**Thomas D. O'Rourke**, Professor, School of Civil and Environmental Engineering, Cornell University, testified before Congress on "National Earthquake Hazards Reduction Program: Past, Present and Future" in 2003. He also presented "The Turkey, Taiwan, and Mexico City Earthquakes: Lessons Learned" to Congress in 1999.

**Kathleen Tierney**, Sociology Professor and Director of the Natural Hazards Research and Applications Information Center, University of Colorado at Boulder, testified before Congress in 2003 on "The Human Dimension of Disasters: How Social Science Research Can Improve Preparedness, Response, and Recovery."

### American Society for Civil Engineers (ASCE) Medals and Awards

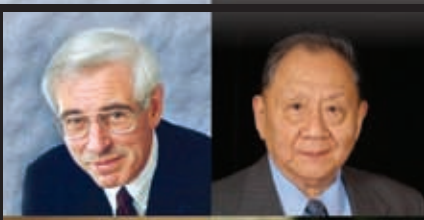
**Masanobu Shinozuka**, Professor and Chair, Department of Civil and Environmental Engineering, University of California at Irvine, received the Scanlan Medal in 2006.

**Mircea Grigoriu**, Professor, School of Civil and Environmental Engineering, Cornell University, received the Norman Medal in 2005 and the Alfred M. Freudenthal Medal in 2002.

**Thomas D. O'Rourke**, Professor, School of Civil and Environmental Engineering, Cornell University, received the Ralph B. Peck Award in 2005.

**Jeffrey Berman**, Assistant Professor, University of Washington, Seattle, former Ph.D. student and **Michel Bruneau**, Professor, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, received the J. James R. Croes Medal in 2003.

**Tsu T. Soong**, Professor, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, received the Nathan M. Newmark Medal in 2002.







*George C. Lee was honored by the White House in November 2007.*

**George C. Lee**, Professor, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, received the Nathan M. Newmark Medal in 2000.

**Maria Feng**, Professor, Department of Civil and Environmental Engineering, University of California, Irvine, received the Walter L. Huber Civil Engineering Research Prize in 1999.

**Tsu T. Soong**, Professor, Department of Civil, Structural and Environmental Engineering, University at Buffalo, and **B.F. Spencer, Jr.**, Professor, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, won the Norman Medal in 1999.

## Civil Engineering Research Foundation (CERF) Awards

**Michael Constantinou** and **Andrei Reinhorn**, Professors in the Department of Civil, Structural, and Environmental Engineering, University at Buffalo, and **Douglas Taylor**, President and CEO, Taylor Devices, received the Charles Pankow Award for Innovation in 2005.

**Amjad Aref**, Associate Professor, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, received the Charles Pankow Award for Innovation (with New York State Department of Transportation and Industrial partners) in 2000.

**Sarah Billington**, Associate Professor, Department of Civil and Environmental Engineering, Stanford University; formerly Cornell University, received the ARC Career Award: Innovative Materials for Civil Systems Research and Education in 2000.

## Earthquake Engineering Research Institute

**Thomas D. O'Rourke**, Professor, School of Civil and Environmental Engineering, Cornell University, served as President of the Earthquake Engineering Research Institute in 2003-2004.

**Stephanie E. Chang**, Associate Professor, University of British Columbia, received the Shah Family Innovation Prize for her work on the community and economic impacts of water and electric power supply damage from earthquakes in 2001.

**Alma D. Garcia**, an MCEER REU student, won EERI's 2007 undergraduate student paper competition with her paper, "Model for Experimental Seismic Fragility Assessment of Nonstructural Systems in Multistory Buildings." Gilberto Mosqueda, University at Buffalo, was her faculty advisor.

**Mehdi Ahmadizadeh**, a graduate research assistant in the Department of Civil, Structural and Environmental Engineering, University at Buffalo, won EERI's 2006 graduate student paper competition with his paper, "A Comparison Between Passive and Semi-Active Structural Control Systems Using Viscoelastic Fluid Dampers."

**Diego Lopez Garcia**, Pontifical Catholic University of Chile, former Ph.D. Student, Department of Civil, Structural, and Environmental Engineering, University at Buffalo won the 2001 graduate student paper competition with his paper, "A Simple Method for the Design of Optimal Damper Configurations in MDOF Structures."

**Christopher Roth**, former graduate research assistant, School of Civil and Environmental Engineering,

Cornell University, won the graduate student paper competition in 1999 for his paper, "Logic Tree Analysis of Secondary Nonstructural Systems with Independent Components."

## EERI Distinguished Lecturers

**Ronald T. Eguchi**, President and CEO of ImageCat, Inc. was the 2008 Distinguished Lecturer. His talk, "Earthquakes, Hurricanes and Other Disasters: A View from Space," focused on the integration of remote sensing technologies in all aspects of disaster management.

**Kathleen J. Tierney**, Director of the Natural Hazards Research and Applications Information Center and Professor of Sociology at the University of Colorado, Boulder, was the 2006 Distinguished Lecturer. Her talk, entitled "Expanding Boundaries: The Value of Multidisciplinary and Interdisciplinary Research for Disaster Loss Reduction," focused on the human and social dimensions of hazards, disasters and risk.

**William J. Petak**, recently retired from the School of Policy, Planning and Development at the University of Southern California, was the 2003 Distinguished Lecturer. His talk, entitled "Earthquake Mitigation Implementation: A Socio-technical System Approach," was largely based on his work with Daniel J. Alesch on the development of integrated decision support systems for acute care facilities.



*Tom O'Rourke (left) and Larry Reavseley (right), with Priscella Nelson in the second row at the NEHRP reauthorization hearings in 2003.*





# RESILIENCE GOING FORWARD – MULTIPLE HAZARD DESIGN

## *Earthquake Engineering to Extreme Events*

On September 11, 2001, our nation was confronted by a new type of hazard as international terrorism struck within our borders with the attack on New York City's twin towers that claimed nearly 3,000 lives. Other disasters have since laid claim to America's infrastructure, its people and their way of life. Can knowledge, tools and technologies generated to enhance resilience against earthquakes serve to advance America's resilience to other threats?

## **Resilience Against Multiple Hazards and Extreme Events**

Equipping organizations and communities with knowledge, tools and technologies that enable them to stand strong and bounce back when disaster strikes is the driving force behind MCEER's concept of resilience and every aspect of the Center's research, education and outreach strategy. Although developed specifically to reduce damage and losses from earthquakes, MCEER's concept of resilience adapts well to any hazard, and thus, is the foundation of several recent projects that address other forms of disaster.

## **Methodology**

Following the attacks on the World Trade Center, MCEER began to investigate the inter-relationship between various types of disasters, the impacts they can have on infrastructure, and the type of technologies that can be used to enhance infrastructure resilience against extreme events. The research challenge is to identify the technologies that can serve the broadest possible multi-hazard protection agenda for a variety of critical infrastructures. Then, natural synergies that exist across hazards will become obvious, and multidisciplinary teams needed to develop integrated solutions can be identified.

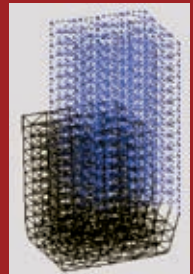
As shown in the following pages, MCEER has started to investigate how multi-hazard solutions can emerge from the knowledge generated by the earthquake engineering community. The problem is being approached from a wide range of perspectives, in order to discover where some promising strategies and solutions may exist. Note that only results from the NSF-funded efforts are provided here; however, similar multi-hazard initiatives are being explored with support from other sponsors.

# INTENTIONAL DISASTERS

In a very real sense, the September 11, 2001 tragedy in New York City, the nature of the damage that occurred, the challenges that the city's emergency response faced, and the actions that were undertaken to meet those demands can be seen as a "proxy" – albeit a geographically concentrated one – for what a major earthquake can do in a complex, densely-populated modern urban environment. Like an earthquake, the terrorist attack occurred with virtually no warning. As would be expected in an earthquake, fires broke out and multiple structural collapses occurred. As has been observed in major urban earthquakes and in other types of disasters, structures housing facilities that perform critical emergency functions were destroyed, heavily damaged, or evacuated for life-safety reasons. Additionally, because the majority of the damage occurred to relatively new and well-engineered structures and because the emergency response system in New York City was considered very well prepared for all types of emergencies, particularly terrorist attacks, the attack and its aftermath provided a useful laboratory for exploring a variety of engineering and emergency management issues.

*How can computer algorithms developed for seismic analysis be adapted to model progressive collapse of buildings due to a variety of hazards?*

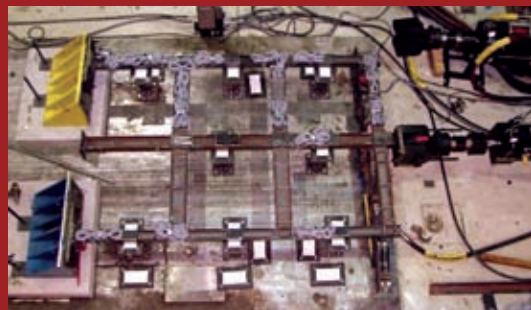
MCEER research has led to the development of a computational platform (based on a Hamiltonian formulation) suitable for modeling and analysis of the progressive collapse of structures subjected to any severe hazard. This project demonstrates the feasibility and efficiency of the formulation, the scalability of the approach and the versatility of the product which can be integrated with numerous commercial programs. An example of a collapse of a 16 story building is shown in the figure.



*Reinhorn, Technical Report in Preparation*

*Can earthquake engineering design details be used to prevent blast-induced progressive collapse of buildings?*

MCEER investigators have studied progressive collapse of earthquake-resistant steel buildings under multi-hazard extreme loading, specifically considering the case of a structure that has suffered loss of a column. A conventional moment resisting steel frame and a novel post-tensioned energy dissipating moment frame, designed for seismic loading, were subjected to "pushdown" testing until collapse. The results of this work demonstrate the ability of innovative post-tension systems to be less prone to collapse than conventional frames. A plan view of the setup for the push-down tests is shown in the accompanying photograph.

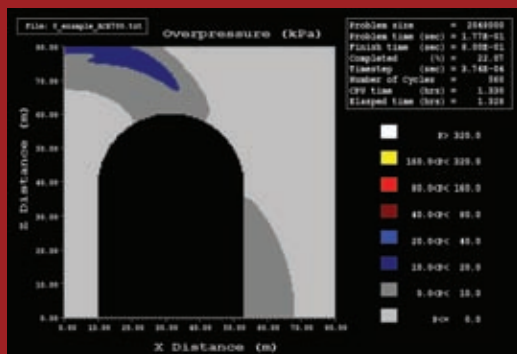


*Mosqueda, Technical Report in Preparation*



### Can seismically isolated structures (such as nuclear power plants) be resilient to blast loads?

This study has developed a new seismic performance assessment procedure for safety-related nuclear structures, and demonstrated the benefits of seismic isolation in terms of substantially reduced spectral demands on critical secondary systems in nuclear structures. Analysis of conventional and isolated nuclear containment vessels shows that the implementation of seismic isolation does not increase the vulnerability of a containment vessel for airblast loadings and mitigates the effects of ground shock loading. The accompanying figure shows a sample profile of airblast overpressure acting on a containment vessel.



Whittaker, MCEER-08-0019

### Can seismic jacketing technology be adapted for blast protection?

Similar to the jacketing concept used for seismic strengthening of bridge piers, MCEER investigators have developed an innovative concept using layers of water or sand wraps to allow for energy dissipation and blast mitigation in piers. This innovative approach relies on phase-change of the filler materials. Tests demonstrate the effectiveness of the concept in reducing damage. The ProJack-M3 concept (left); and energy absorption by a stack of 5-tiles without (center) and with a 1-inch layer of water (right) is shown below.



Saadeghvaziri, Technical Report in Preparation

### Can Steel Plate Shear Walls (SPSWs) designed for earthquake resistance add blast protection to buildings?

From a structural engineering perspective, blast is the extreme event whose impact on infrastructure most closely resembles that of earthquakes. MCEER research on new SPSW systems for seismic regions has led to further studies to investigate their blast resistance. MCEER research demonstrates that SPSWs can be designed to have some level of blast resistance, but that new plate connection details are needed to achieve the ultimate blast performance that is theoretically possible for this system. The photos below show large deformations (left), and failure (right) of SPSW infill plates under small and large blast charges, respectively.



Bruneau, Technical Report in Preparation



# NATURAL DISASTERS

Much of the physical damage to infrastructure and disruption to social and economic systems following Hurricane Katrina resembled the aftermath of a major earthquake. Significant damage to engineered infrastructure including levees, commercial and public buildings, roads and bridges, utility distribution systems for electric power and water, waste water collection facilities, and vital communication networks was observed. Damage to critical infrastructure such as hospitals and communication systems crippled the affected communities, and more importantly, the response and recovery efforts following the hurricane.

MCEER researchers are working toward synthesizing the lessons learned from this disaster with prior observations from earthquake reconnaissance to develop effective measures for damage mitigation and improved response and recovery efforts. By collecting and analyzing this multi-hazard information, MCEER is seeking to develop engineering design strategies and organizational strategies that will make communities more resilient against natural disasters.

## *Can advancements in remote sensing technologies for earthquake loss estimation be used to help assess vulnerability to threats from other extreme events?*

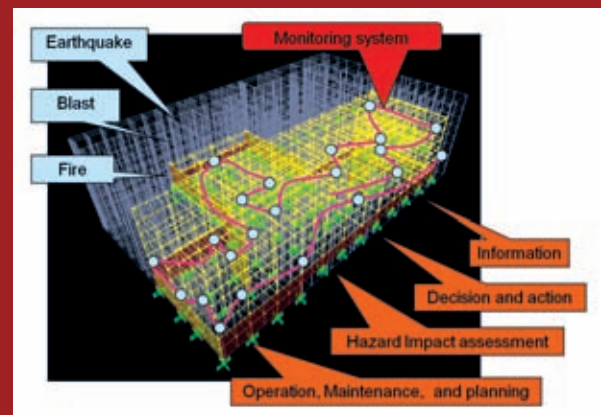
Accurately characterizing the structure of high-risk cities is integral to assessing and mitigating the vulnerability of critical facilities and lifelines. MCEER researchers have developed building inventory models and a suite of techniques (such as high-resolution satellite imagery to classify buildings by structural or construction type; an object-oriented image processing methodology to automatically extract building outlines and square footages for residential, commercial and industrial structures) that contribute to pre- and post-disaster resourcefulness, by facilitating advanced scenario testing, loss estimation and threat assessment within urban environments. These tools are location and hazard independent, and could be integrated into multi-hazard risk models for events including blast, chemical weapon and natural disasters around the world. An example of a 3D model created using stereo imagery for an area east of Kanazawa-bunko station, Yokohama, Japan is shown below.



Eguchi and Adams, MCEER-08-0020

## *Can knowledge of critical facilities and systems learned in earthquake studies improve understanding of the performance of these systems in other disasters?*

MCEER researchers have developed a software tool that simulates the integrated response of complex systems within a hospital subjected to fire, blast or earthquake. The software platform also simulates cascading consequences from impacts of the initial hazard and organizational decisions toward addressing it. The software includes modules for facility system management, hazard simulation, hazards impact analysis, facility system monitoring, and evacuation analysis. The figure below shows the impact of various hazards to a five-story hospital building in New York State.



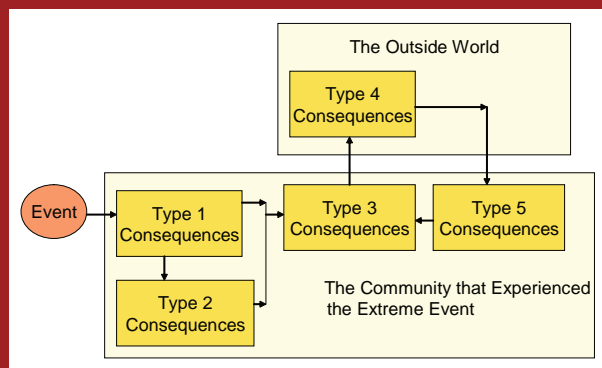
Lee, Technical Report in Preparation





## Can lessons learned from post-earthquake recovery be used to model community recovery from other disasters?

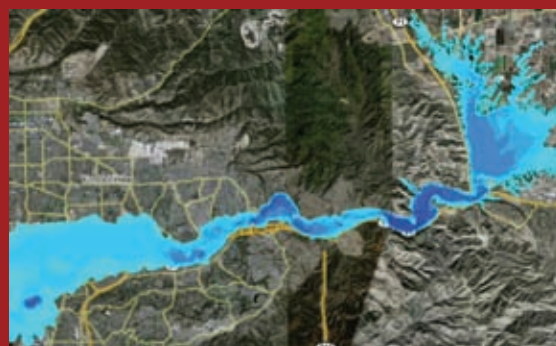
This research has developed a conceptual model of communities as self-organizing systems, and of recovery processes following disasters. It involves simplified computer models of communities employing cellular automata, agent-based fractals, and self-organizing systems. It represents a breakthrough in understanding how extreme events result in community disasters and in conceptualizing and simulating recovery processes. It also serves as a basis for evaluating interventions to facilitate community social and economic recovery.



Alesch and Petak, Technical Report in Preparation

## How would a seismically-induced earth dam breach impact human casualties, property loss, surface transportation and utility networks installed in low areas?

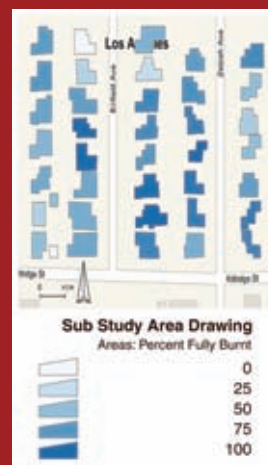
A two-dimensional (2D) flood simulation model was developed to predict the impact of catastrophic flooding on buildings and city streets, and to support emergency planning and decision making. Significant differences in results compared to those obtained from commonly used 1-D analyses raise questions on the reliability of predictions based on state-of-practice models for dam-safety purposes.



Sanders, Technical Report in Review

## How can studies of post-earthquake fire advance modeling of fire ignition and spread?

MCEER research has focused on statistical modeling of post-earthquake fire ignitions and simulation modeling of post-earthquake fire spread. Generalized models have been fit to data from recent California earthquakes for the first time, resulting in models that can be used to predict the number of ignitions in each census tract in a future earthquake. The new post-earthquake urban fire spread simulation model uses actual building footprints and heights from remote sensing data, and explicitly models the different modes of fire spread from room to room and building to building (e.g., burn through walls, radiation from roof flames, and branding). The figure shows the percentage of burned buildings after four hours in a small area of Los Angeles.



Davidson, Technical Report in Review





# MCEER PUBLICATIONS RESULTING FROM NSF SPONSORSHIP

## Enabling a New Breed of Lifelines

"Seismic Response Modeling of Water Supply Systems," by P. Shi and T.D. O'Rourke, 5/5/08, MCEER-08-0016.

"Seismic Performance Evaluation of Water Supply Systems," by Y. Wang and T.D. O'Rourke, 5/5/08, MCEER-08-0015.

"Seismic Evaluation and Rehabilitation of Critical Components of Electrical Power Systems," S. Ersoy, B. Feizi, A. Ashrafi and M. Ala Saadehvaziri, 3/17/08, MCEER-08-0011.

"Fragility Analysis of Water Supply Systems," by A. Jacobson and M. Grigoriu, 3/10/08, MCEER-08-0009.

"Experimental and Analytical Studies of Base Isolation Systems for Seismic Protection of Power Transformers," by N. Murota, M.Q. Feng and G-Y. Liu, 9/30/05, MCEER-05-0008.

"Behavior of Underground Piping Joints Due to Static and Dynamic Loading," by R.D. Meis, M. Maragakis and R. Siddharthan, 11/17/03, MCEER-03-0006.

"Proceedings of the Eighth U.S.-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Liquefaction," edited by M. Hamada, J.P. Bardet and T.D. O'Rourke, 6/30/03, MCEER-03-0003.

"Proceedings of the Seventh U.S.- Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction," edited by T.D. O'Rourke, J.P. Bardet and M. Hamada, 11/19/99, MCEER-99-0019.

"Response of Buried Pipelines Subject to Earthquake Effects," by M.J. O'Rourke and X. Liu, ISBN-0-9656682-3-1, 1999, MCEER-99-MN03.

"Proceedings of the Workshop on Performance Criteria for Telecommunication Services Under Earthquake Conditions," edited by A.J. Schiff, 7/15/98, MCEER-98-0008.

"Engineering and Socioeconomic Impacts of Earthquakes: An Analysis of Electricity Lifeline Disruptions in the New Madrid Area," edited by M. Shinozuka, A. Rose, and R.T. Eguchi, ISBN-0-9656682-2-3, 1998, MCEER-98-MN02.

## A Transformational Concept for Structural Resilience of Hospitals

"Evolutionary Methodology for Aseismic Decision Support," by Y. Hu and G. Dargush, 12/15/08, MCEER-08-0029.

"New Experimental Capabilities and Loading Protocols for Seismic Quantification and Fragility Assessment of Nonstructural Systems," by R. Retamales, G. Mosqueda, A. Filiatrault and A.M. Reinhorn, 11/24/08, MCEER-08-0026.

"Development, Implementation and Verification of Dynamic Analysis Models for Multi-Spherical Sliding Bearings," by D.M. Fenz and M.C. Constantinou, 8/15/08, MCEER-08-0018.

"Numerical and Experimental Studies of Self-Centering Post Tensioned Steel Frames," by D. Wang and A. Filiatrault, 5/12/08, MCEER-08-0017.

"Structural and Nonstructural Earthquake Design: The Challenge of Integrating Specialty Areas in Designing Complex, Critical Facilities," by W.J. Petak and D.J. Alesch, 4/30/08, MCEER-08-0014.

"Seismic Behavior and Design of Boundary Frame Members of Steel Plate Shear Walls," by B. Qu and M. Bruneau, 4/26/08, MCEER-08-0012.

"Experimental Investigation of Full-Scale Two-Story Steel Plate Shear Walls with Reduced Beam Section Connections," by B. Qu, M. Bruneau, C.H. Lin and K.C. Tsai, 3/17/08, MCEER-08-0010.



"Mechanical Behavior of Multi-Spherical Sliding Bearings," by D.M. Fenz and M.C. Constantinou, 3/6/08, MCEER-08-0007.

"Experimental Seismic Performance Evaluation of Isolation/Restraint Systems for Mechanical Equipment – Part 2: Light Equipment Study," by S. Fathali and A. Filiatrault, 12/13/07, MCEER-07-0022.

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"Passive Energy Dissipation Systems for Structural Design and Retrofit," by M.C. Constantinou, T.T. Soong, and G.F. Dargush, ISBN-0-9656682-1-5, 1998, MCEER-98-MN01.

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"The 921 Chi-Chi Taiwan Earthquake of 1999 Collection," MCEER, 12/2000, MCEER-00-SP03.

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"Quindío, Colombia Earthquake of January 25, 1999: Reconnaissance Report," by A.P. Asfura and P.J. Flores, 10/4/99, MCEER-99-0017.

"The New York City Seismic Code: Local Law 17/95," New York City Seismic Code Committee, 7/28/99, MCEER-99-SP06.

"MCEER/NCREE Response: Preliminary Report from the MCEER-NCREE Workshop on the 921 Taiwan Earthquake," by G.C. Lee, M. Bruneau, I.G. Buckle, S.E. Chang, P.J. Flores, J.D. Goltz, T.D. O'Rourke, M. Shinozuka, T.T. Soong and L. Taddeo, 10/99, MCEER-99-SP03.

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