National Science Foundation Investment
in
Earthquake Engineering Research Centers (EERCs)

The purpose of this report is to analyze and document the impact of the investment made by the Directorate for Engineering of the National Science Foundation (NSF) in three Earthquake Engineering Research Centers established in 1997.

Vilas Mujumdar
Program Director
Engineering Education and Centers Division
Directorate for Engineering
National Science Foundation

Nov. 1, 2008

EXECUTIVE SUMMARY OF IMPACT

Three earthquake engineering research centers funded by the National Science Foundation have had a significant impact on the practice of earthquake engineering, loss assessment due to earthquakes, education of students in earthquake engineering, and more significantly on developing and implementing the interdisciplinary methodology of research incorporating such diverse disciplines as structural engineering, geotechnical engineering, information technology, and social sciences. Overall the three centers have made significant contributions to the understanding of phenomena of major earthquakes and their impact on society, developing technologies to reduce earthquake event related losses, and creating tools to develop resiliency in the communities to deal with these events. Some of the broader impacts, specific technologies and outcomes are briefly described below. Some more details are given in the text of this report and further details are available in the reports submitted by each center.

Multi-disciplinary Center for Earthquake Engineering Research (MCEER) – University at Buffalo, NY

This center developed the concept of resiliency in the community and defined its dimensions to provide enhanced seismic resilience of communities through improved engineering and management tools in three areas: *critical infrastructure systems (water supply, electric power), acute care hospitals, and emergency management functions.*

- Developed analytical, experimental and empirical procedures to evaluate and enhance the *seismic resilience of lifeline systems*. Specifically, developed 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 modeling procedure, that emphasizes understanding how mitigating lifeline infrastructure systems can improve the disaster resilience of a community. These models *"Comprehensive Model for Integrated Electric Power Systems"* and a "*Comprehensive Model for Integrated Water Supply Systems"* are being used in the nations largest metropolitan area, Los Angeles by the Los Angeles Department of Water and Power for their system-wide planning and engineering.
- 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. 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 no loss of function requires that engineering solutions not only address the structural systems, but also the nonstructural components (electrical, mechanical, and medical equipment, piping, contents, etc.). More robust and *redundant* physical systems (and health care provider organizations) can more *rapidly* recover and regain functionality. MCEER developed 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 advanced codes and guidelines.

    - Two decision support platforms were developed to integrate these findings. The *Rehabilitation Decision Analysis Toolbox (RDAT)*, built on a user-friendly MATLAB interface, provides an integration framework based on a fragility approach. The *Evolutionary Aseismic Design and Retrofit (EADR)* software uses an evolutionary analysis procedure for structural systems, which incorporates advanced protective technologies in an uncertain seismic environment and can integrate multiple flexible constraints and rules including non-engineering organizational and socio-economic constraints.
- In the emergency management functions, rapid response and recovery are emphasized. MCEER 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.
    - A range of remote sensing technologies, including synthetic aperture radar, higher solution optical satellite imagery, and GPS-based tools with advanced GIS and improved database management systems are utilized.
    - A multi-year effort led to the development a new post-earthquake reconnaissance tool called VIEWS™, Visualizing the Impacts of Earthquakes with Satellites, and the fielding of a set of tools called the “Virtual Reconnaissance Survey” (VRS), which allows researchers to share spatially-referenced disaster impact data online through a web browser.

Mid-America Earthquake (MAE) Center – University of Illinois-Urbana Champaign, IL

This Center focused on establishing a complete framework and application tools for Consequence-based Risk Management (CRM) and its IT-platform- MAEviz, deployment to successfully address the challenges of earthquake impact assessment, mitigation, response and recovery for the portfolios of its partners in industry, State, Federal and international agencies and organizations in the Central USA. It is postulated that the balance between annual earthquake hazard and potential losses in the Central USA is similar to that on the West Coast, due to the potentially catastrophic effects of a major earthquake on the New Madrid fault system. *MAE Center has developed suitable system-level procedures and application cases that have made a measurable difference to the region and its ability to respond to a catastrophic earthquake.*

The MAE Center characterized the hazard in the Central USA comprising eight states generally known as New Madrid Seismic Zone (NMSZ) which was not done before, a significant contribution to understanding the New Madrid fault mechanisms. Overall the focus of the Center has been in three areas: *defining hazard; generate inventory of all assets in a specified region; and developing vulnerability functions.* Social impacts are modeled including damage to infrastructure. All of these efforts are bundled in MAEviz platform.

The IT platform MAEviz has been developed both as a conduit for delivering its products and a system-level research prioritization tool. MAEviz is now fully operational as a stat-of-the-art assessment and decision-making web-enabled tool that includes the most up-to-date methods, models and data for earthquake risk management. This is perhaps the only unique tool which allows the visualization of earthquake damage using different scenarios thus enabling making an effective risk-informed decision. MAEviz platform has been used in,

- The Regional (Memphis) test bed for a site-specific impact assessment on Memphis and Shelby County;
- The Thematic (Transportation) test bed where transportation network models, bridge fragility, and functionality are employed to assess the transportation network in Charlestown;
- The Organizational (Emergency Management Agencies) test bed for emergency management authority in Illinois.

In addition to its application in testbeds, MAEviz has been used by utility companies and state agencies. It also been used internationally to assess earthquake losses—e.g., in Istanbul, Turkey—and is proposed for use in Indonesia.

Pacific Earthquake Engineering Center (PEER) – UC-Berkeley, CA

PEER Center concentrated on the development of performance-based earthquake engineering (PBEE) technology for design and evaluation of buildings, lifelines, and infrastructure to meet the diverse seismic performance objectives of individual stakeholders and society.

PEER Center developed and disseminated procedures and supporting tools and data for performance-based earthquake engineering (PBEE) aimed at cost-effective reduction of earthquake losses, with emphasis on the following areas:

- Definition of seismic hazard for engineering design applications;
- Engineering tools for the seismic assessment and design of constructed facilities, with emphasis on geotechnical structures, buildings, bridges, and lifelines;
- Design criteria to ensure safe and efficient performance of constructed facilities;
- Methodologies including engineering and public policy instruments for mitigating seismic hazards in existing buildings; and
- Performance-based approaches for design and evaluation of constructed facilities to provide appropriate levels of safety for occupants, and protection of economic and functional objectives for essential facilities and operations.

The overall approach is aimed at improving decision making about seismic risk by making the choice of performance goals and the trade-offs that they entail apparent to facility owners and society at large. The approach has gained worldwide attention in the past decade with the realization that earthquakes in developed countries impose substantial economic and societal risks above and beyond potential loss of life and injuries. PEER Center has developed quantitative tools for characterizing and managing these risks to address diverse economic and safety needs. In specifics, three levels of decision-making are addressed:

One level is that of owners or investors in individual facilities (e.g., a building, a bridge) who face decisions about risk management as influenced by the seismic integrity of a facility.

A second level is that of owners, investors, or managers of a portfolio of buildings or facilities—a university or corporate campus, a highway transportation department, or a lifeline organization—for which decisions concern not only individual structures but also priorities among elements of that portfolio.

A third level of decision-making is concerned with the societal impacts and regulatory choices relating to minimum performance standards for public and private facilities. The overall impact of PEER Center’s work has been summarized by the California Seismic Safety Commission (CSSC), which stated:

- PEER is the primary earthquake engineering research arm of the State of California.
- PEER's efforts have produced cost-effective products that benefit the State of California and are consistent with the goals and initiatives of the California Earthquake Loss Reduction Plan.

Although the CSSC is concerned with California, the impact of PBEE is national and international and can be been considered as the next generation of earthquake engineering Practice as it allows risk-informed decisions based on expected performance of buildings and infrastructure rather than on code specified values of loads and materials.

Summary of Impact on Education

Students have been educated with a multidisciplinary education in loss assessment methodologies and tools and readily understand and acknowledge that emergency preparedness and management projects are multidisciplinary in nature, are able to work with multiple disciplines towards a common goal, and that, because of their multidisciplinary perspectives, these graduates are more adept at bridging work by academia, private sector, researchers, and specialized research centers, representing a better understanding of the broader picture/total perspective, from science to policy. Many courses related to broader area of earthquake hazard risk mitigation are developed. For example: A graduate course “Consequence–Based Risk Management” is now available from UIUC as a capstone for presenting the body of knowledge supporting this new technological framework. The course reflects the interdisciplinary nature of earthquake engineering practice and research and provides an overview of diverse topics related to hazard definition, vulnerability assessment, mitigation measures and economic/societal impact. Specific courses for practicing professionals are also developed. Examples of such courses include PEER Center’s presentation at the EERI Technical Seminar Series entitled, “Soil-Structure Interaction for Performance-Based Earthquake Engineering,” offered in March 2007 in Seattle, San Francisco, and Los Angeles, and the PEER Workshop on Ground Motion Selection and Modification offered in November 2007 and January 2008 at UC Berkeley.

International seminars and workshops have given undergraduate and graduate students the chance to meet with their peers from other countries, to set the stage for future research collaborations. Many graduates were hired by the industry and academic institutions. Several graduates are working in academia mentoring other students in earthquake engineering discipline and interdisciplinary research.

IMPACT OF THE EARTHQUAKE ERCs

Background

In 1986, following a national competition, NSF funded one earthquake engineering research center, called National Center for Earthquake Engineering Research (NCEER) at the State University of New York at Buffalo for an initial period of five years. The award was subsequently renewed for another five years. In October 1996, Division of Civil and Mechanical Systems (CMS) in the Directorate for Engineering announced a new competition to establish earthquake engineering research centers to be funded through Earthquake Hazard Mitigation Program (EHM). EHM was a participant in the multiagency National Earthquake Hazards Reduction Program (NEHRP). This solicitation for new competition specifically identified some of the key features of the program, that are: *earthquake hazard mitigation as a multidisciplinary problem including structural engineering, geotechnical engineering, architecture, planning, and the social sciences; education of next generation of researchers and practitioners; outreach to industry, government, precollege schools and potential user groups ;integrated approach to research; in general a more holistic approach to knowledge discovery.*

Based on the careful review and evaluation of proposals received, NSF's Directorate for Engineering awarded three Earthquake Engineering Research Centers (EERCs) in 1997, rather than continuing with only one center at the State University of New York at Buffalo. The awards were made to three lead institutions: State University of New York at Buffalo (SUNY-Buffalo), University of Illinois at Urbana-Champaign (UIUC), and the University of California-Berkeley (UC-Berkeley). Each of these lead institutions was joined by many other universities as partners. Three centers were titled as follows:

1. Multi-disciplinary Center for Earthquake Engineering Research (MCEER) – SUNY-Buffalo, NY
2. Mid-America Earthquake (MAE) Center – UIUC, IL
3. Pacific Earthquake Engineering Center (PEER) – UC-Berkeley, CA

Introduction

Oversight of the Engineering Earthquake Engineering Research Centers (EERCs)

Each award is a cooperative agreement between the lead institution and NSF. After the awards of the Centers, for one year, the oversight of these three centers was the responsibility of CMS division. In 1999, this responsibility was officially transferred to the Engineering Education and Centers Division (EEC) of the Directorate for Engineering for the following reasons:

- Experience with management of cross-disciplinary research center programs designed to achieve deliverables
- Experience with centers designed to move fundamental research to proof-of-concept in testbeds to speed technology transfer
- Development of strategic research planning in academe

- Experience with formation of cross-disciplinary teams in academic research
- Experience with the integration of research and education
- Experience with modes of stimulating and facilitating partnerships with industry and other users
- Experience with modes of stimulating and facilitating partnerships with industry and other users
- Time proven, effective systems of funding and post-award review and oversight

Since 1999, the oversight has been provided by EEC. Two centers, PEER, and MCEER graduated in Oct. 2007. MAE Center was given one-year extension and will be graduating in Oct. 2008. The vision, the goals and accomplishments of each center are briefly described below:

Earthquake Engineering Research Centers (EERCs)

Multidisciplinary Center for Earthquake Engineering Research (MCEER) – SUNY-Buffalo, NY

MCEER requested a 90-day 'no-cost' extension and was granted. The final report was submitted by MCEER to NSF on May 31, 2008. At the graduation stage, MCEER's key management included Prof. Michel Bruneau, Director, Prof. Andre Filiatrault, Deputy Director, Mr. Donald Goralski, Industrial Liaison Officer, and Prof. S. Thevanayagam, Education Program officer, and several thrust leaders. At the graduation stage, MCEER's core partner institutions were: *Cornell University; University of California at Irvine; and University of Colorado at Boulder*. At various stages in the life of the Center, fourteen academic institutions served as research/outreach partners, twenty-nine companies as industrial partners, three utility companies, and six city, and state government agencies as partners.

Vision

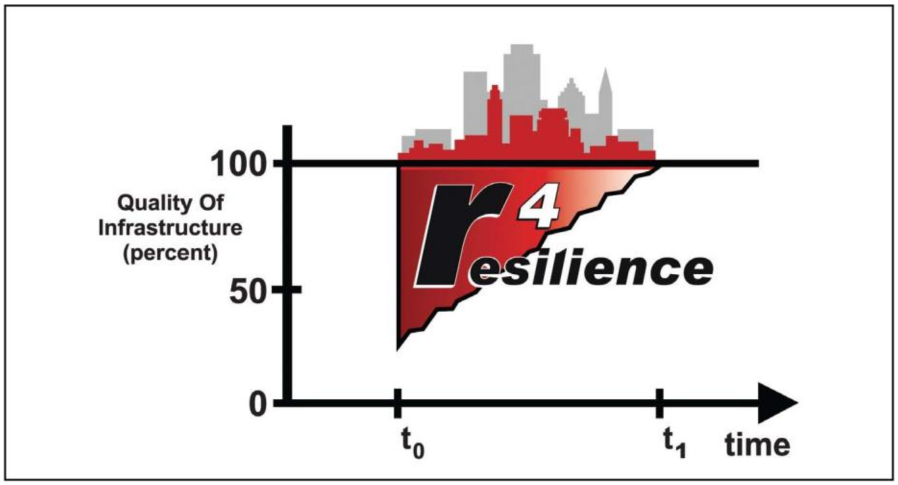
The ultimate vision of MCEER is to help establish earthquake resilient communities. To accomplish this, MCEER also crafted a mission statement, noted below:

Mission

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.

Research Program

To fulfill its vision of achieving disaster resilient communities, MCEER designed a comprehensive research program. To quantitatively define resilience, three desired outcomes are proposed: *reduced probability of system failure, reduced consequences due to failure, and reduced time to system restoration.* MCEER's work also focuses on improving the resilience of facilities and organizations whose functions are essential for community well-being after an earthquake and/or other disaster. The facilities that are considered critical for this well-being are: water and power lifelines, acute care facilities (hospitals), and organizations that are responsible for emergency management at the local level.



Lack of resilience is represented by the red triangle above. When disasters strike (t0), damage to critical infrastructure results in diminished performance. Over time (at t1), infrastructure is restored to its original functionality

The research activities are expected to have impact globally in seismic resilience. In brief summary, these activities are described below:

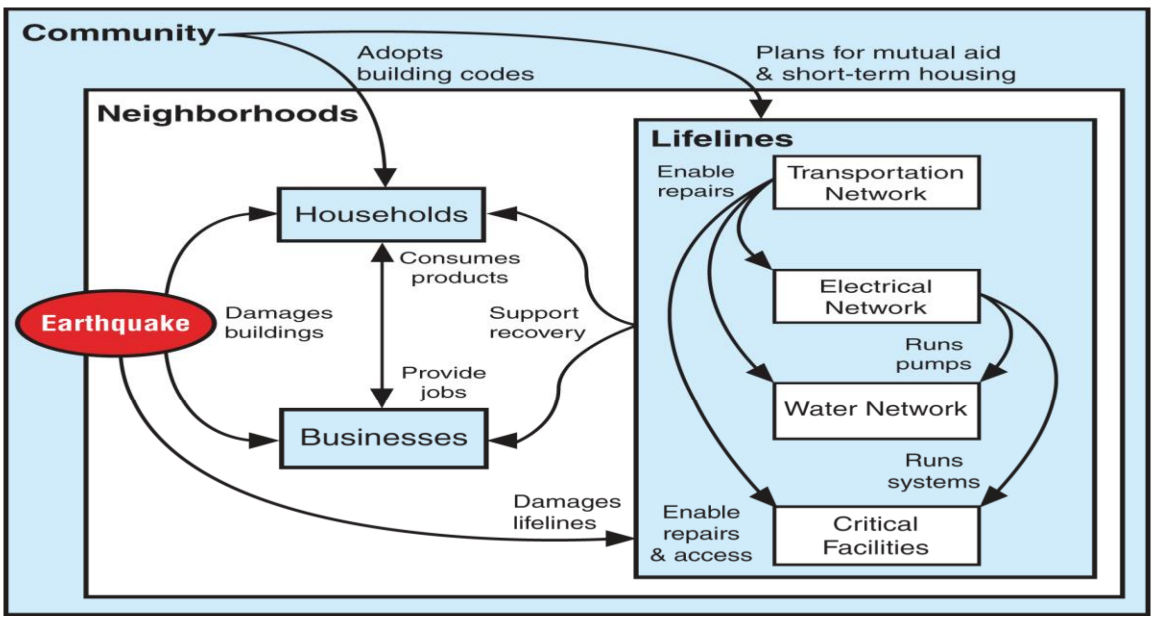
- Development of analytical, experimental and empirical procedures to evaluate and enhance the seismic resilience of lifeline systems. These studies include the development of improved models of the post-earthquake restoration processes for electric power and water supply systems; the development of 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 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 acute care facilities from the effects of earthquakes. The results are used to provide meaningful input to integrated decision support tools. Studies include development of new materials and technologies for the seismic retrofit of a wide variety of structures and nonstructural 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 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. Studies include 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.

Properties of Resilience

MCEER defines four fundamental properties of disaster resilience characteristics.

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



The community recovery model emphasizes recovery time, spatial disparities, and linkages between different sectors of a community

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.

Dimensions of Resilience

In addition to the aforementioned properties of resilience, MCEER's framework includes the following 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 total physical systems (including all 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.

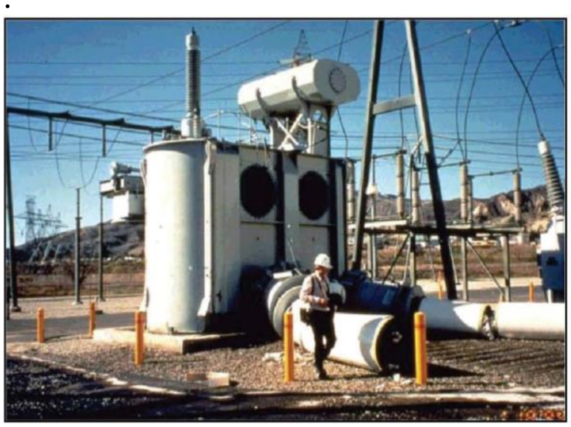
Impact

MCEER has successfully accomplished its mission of enhancing seismic resilience of communities by focusing on two areas of critical infrastructure that are of vital importance during and aftermath of a major earthquake hazard event, namely *water and power lifelines, and acute care hospitals.*

MCEER has developed the advanced knowledge and technologies needed to achieve integrated engineering tools, decision support systems, and related techniques and procedures that can provide cost-effective quantitative enhancements of the seismic resilience of these highly critical infrastructures. These tools and technologies make it possible to make more rationally-based investments and allocations of finite resources, and also quantify the expected outcomes in forms that can be communicated to the public and policy makers. This newly generated knowledge also helps engineers to better anticipate and adjust the outcomes of their designs for different hazard scenarios and apply appropriate loss-reduction measures working with their clients. MCEER's research also makes it possible for emergency management agencies to develop more reliable post-earthquake scenarios and to optimize their response and recovery activities through the use of advanced technologies and decision support systems enhancing post-disaster response and accelerating the time to recovery after a major earthquake event.

More specifically, research on electrical power and water delivery systems, together with transportation systems, focuses on problems germane to the infrastructural backbone of all communities

.



MCEER's electric power and water delivery systems research addresses problems germane to the infrastructural backbone common to all communities

Research on acute care facilities focuses on issues related to highly complex physical and organizational structures that must provide essential services following earthquakes. Decision support systems anchored in resilience concepts, are being used by the industry and government organizations such as the Los Angeles Department of Water and Power, and the California Office of Statewide Health Planning and Development.

MCEER's research on acute care facilities focuses on complex physical and organizational structures that must be able to provide services following an earthquake.

MCEER teamed with NCREE to investigate damage following the 1999 Chi- Chi earthquake in Taiwan

Technology Transfer

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. MCEER's national Information Service is a comprehensive source for earthquake engineering and loss reduction information, providing reference services including literature searches and document delivery. Information professionals on staff fulfill an average of 200 requests each week, and MCEER's website, offering additional online information and resources, receives more than 56,000 distinct visits annually. MCEER's Quakeline® database, updated monthly and also available online, provides easy access to tens of thousands of records on books, journals, technical reports and other earthquake engineering and natural hazards mitigation literature.

The Toggle Brace installed in the Yerba-Buena Tower in San Francisco (new structural damper configurations developed through MCEER research in partnership with industry)

Industry Partnerships

MCEER forged new strategic alliances with manufacturers, consultants, end-users and other public- and private-sector stakeholders to develop, adapt, test and help implement the use of new and emerging technologies to mitigate earthquake losses. The program creates opportunities for cross-participation in collaborative research and demonstration projects enabling partners to examine and assess the reliability of new and emerging technologies, as well as providing access to a variety of research, education and technology transfer opportunities.

Education

Comments and feedback from industry indicate that MCEER students have been educated to readily understand and acknowledge that emergency preparedness and management projects are multidisciplinary in nature, are able to work with multiple disciplines towards a common goal, and that, because of their multidisciplinary perspectives, these graduates are more adept at bridging work by academia, private sector, researchers, and specialized research centers, representing a better understanding of the broader picture/total perspective, from science to policy. 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.

International Collaborations

MCEER has cooperative projects/programs with numerous countries in the world where earthquake resistant design of buildings and infrastructure systems is a concern. The map below shows the countries where an active partnership in earthquake engineering research, education and/or technology transfer activities is taking place. This success is the result of the "center approach" in earthquake engineering pioneered by NSF, where multidisciplinary experts from multiple institutions can 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.

MCEER and NCREE (Taiwan) carried out an experimental program on steel plate shear walls for seismic design and retrofit.

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 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. The U.S. also benefits from the knowledge developed in these countries to help establish earthquake resilient communities throughout the world.

Researchers in the U.S. and Japan have developed case histories of earthquake-induced ground deformations and their effects on lifeline facilities

Mid-America Earthquake Center (MAEC)

MAE Center was granted a one-year extension to their cooperative agreement. The termination of the agreement is Sept. 30, 2008. MAEC also requested a 90-day ‘no-cost’ extension and was granted. The final report must be submitted to NSF no later than Dec. 31, 2008. The analysis in this report is based on their 11th year report to NSF submitted in May 2008. MAEC’s key management included Prof. Amr Elnashai, Director, Mr. Timothy Gress, Director of Business development, and Prof. Philip Gould, Education Program officer, and several thrust leaders. At the graduation stage, MAE Center’s core partner institutions were: *University of Washington; Georgia Institute of Technology; Washington University- St. Louis; Texas A & M University; University of Memphis; University of Texas at Austin; and University of Puerto Rico at Mayaguez.* At various stages in the life of the Center, fourteen academic institutions served as research/outreach partners, twenty-nine companies as industrial partners, three utility companies, and six city, and state government agencies as partners.

Vision

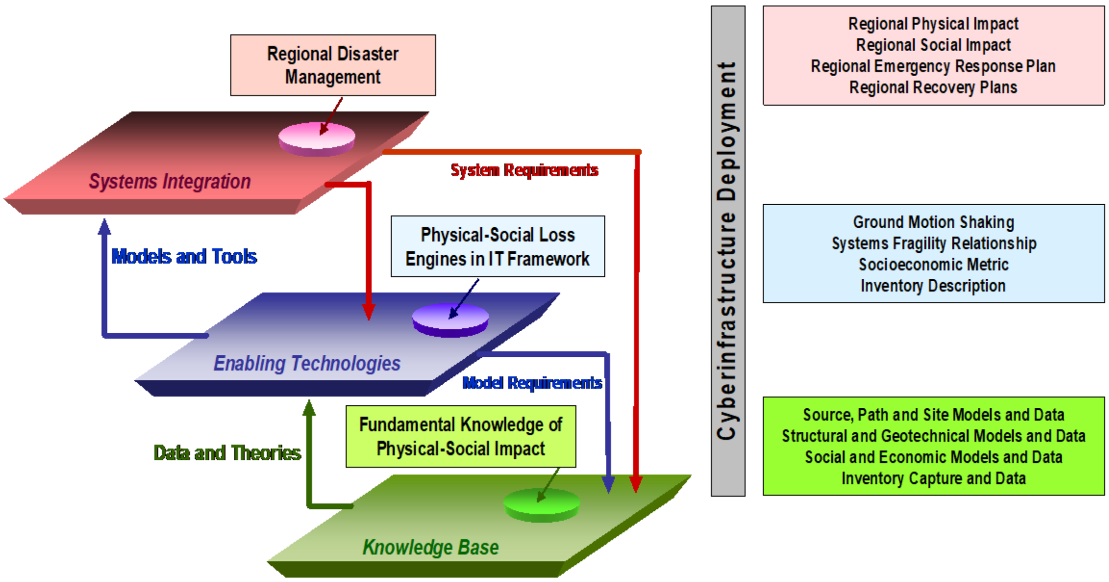
To play an indispensable role in advancing the knowledge of earthquake risk management in the Central and Eastern United States, where the nature of seismic risk requires innovative system-level solutions, intervention prioritization approaches and integration between assessment, mitigation, response and recovery in a total risk management cycle. To become the primary source of earthquake information in the Central United States.

To accomplish this, MAEC developed a mission that can be summarized as follows.

Mission

To develop a complete framework and application tools for Consequence-based Risk Management (CRM) and its IT-platform to address the challenges of earthquake impact assessment, mitigation, response and recovery. To articulate programs in a hierarchical way, starting from the ERC strategic planning framework, adapting it to regional seismic risk management, mapping the operational steps for its ‘Consequence-Based Risk

Management', and leading to the definition of the required projects and the expertise and facilities needed to execute the scope. MAEC developed a strategic plan for CRM using the three-plane chart concept shown below.



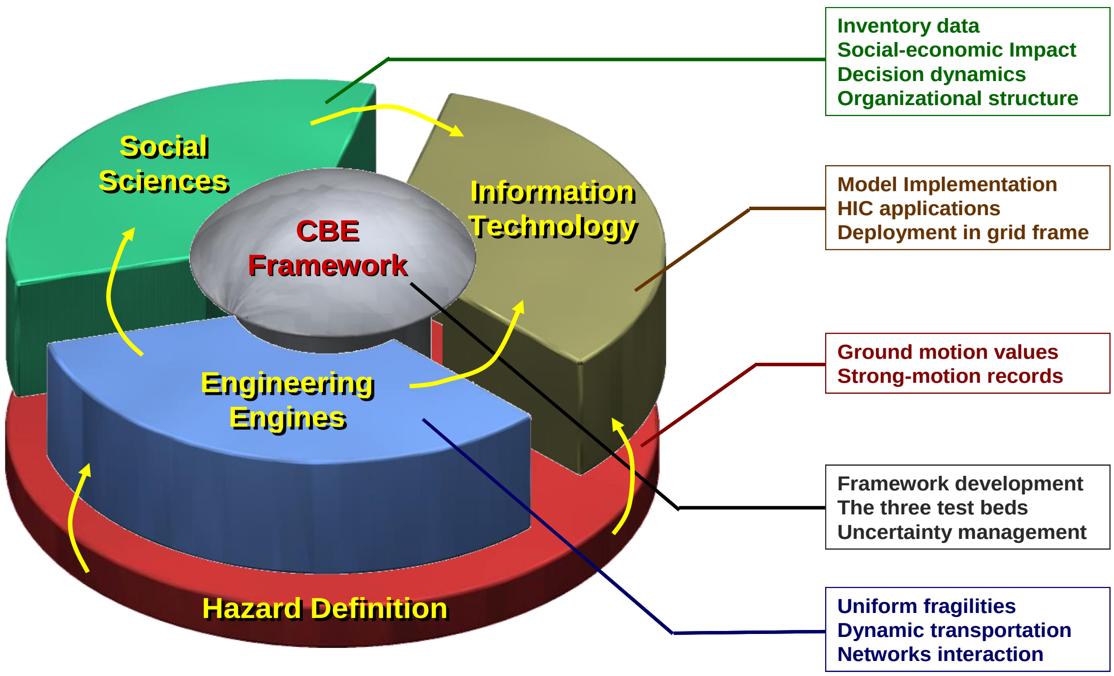
Three-plane Chart leading the Strategic Planning towards Consequence-based Risk Management

Research Program

The MAE Center system-level Consequence-Based Risk Management (CRM) paradigm that embraces the concept of a Total Risk Management Cycle provides a philosophical as well as a practical framework for the assessment of the dynamic interdisciplinary relationship between causes, effects and effect-mitigation, response and recovery features of major event or disaster management. It provides an effective means of drawing emergency plans, responding to disasters and prioritizing intervention for loss reduction. The research program focuses on integrating social science and information technology thrusts with engineering, and geophysics and develops MAEC's understanding, and its ability to support the stakeholders in a logical and comprehensive manner based on recognition of hazard-generated and response-generated consequences. The program also develops Center tools into a final product - a fully functioning MAEviz, an advanced and versatile earthquake impact assessment and decision making web-based interactive system, and its successful application and other impact assessment tools on a large regional scale, comprising the 8 central states.

The four research thrusts of the MAE Center operative in Year 10 remained (i) Consequence-Based Risk Management (CRM) Framework, (ii) Engineering Engines, (iii) Social and Economic Sciences, and (iv) Information Technology. Through the research activities of the MAE Center, particularly the test beds, a wide range of stakeholders continue to be engaged, including federal agencies, state emergency management agencies, federal and state departments of transportation, non-government organizations, utility companies, and private corporations, and several externally funded projects are currently underway, including a catastrophic planning study for the New Madrid Seismic

Zone sponsored by the Federal Emergency Management Agency. The different steps in the research plan are as follows:



Research thrusts and interactions of the MAE Center

- The hazard is derived and modeled in the Hazard Definition (HD) foundation sub-thrust.
- Input motion characterization of all shapes is then fed into the Engineering Engines (EE) thrust, where methods, models and data for the evaluation of physical impact are developed and applied. It is also passed to Information Technology (IT).
- The physical damage is transmitted to the Social-Economic (SE) thrust to quantify the implications of the physical damage on society.
- The hazard, physical impact and social-economic consequences are fed into the Information Technology (IT) thrust for visualization.
- The operations and applications are managed from the top by the Consequence-based Risk Management (CRM) overarching thrust that includes the test beds and the uncertainty management team.

Some key components of the overall research program are briefly described below:

Systematic Treatment of Uncertainty

This project has influenced MAEviz in a major way, rendering it one of the most uncertainty-aware impact assessment platforms available. Algorithms have been developed for incorporating aleatoric and epistemic uncertainties research efforts into MAEViz, which display the contribution of uncertainties due to ground shaking, ground failures, inventory data, structural performances, damage models and loss models to intermediate and final damage and loss estimates. This uncertainty aggregation is necessary to develop appropriate community decision variables and metrics. Significant advance was made in cooperation with Engineering Engines (EE) thrust projects; Vulnerability functions (EE-1) and Advanced Simulation modeling (EE-3) in deriving a new approach for the generation of fragility relationships from pushover curves, with uniform reliability.

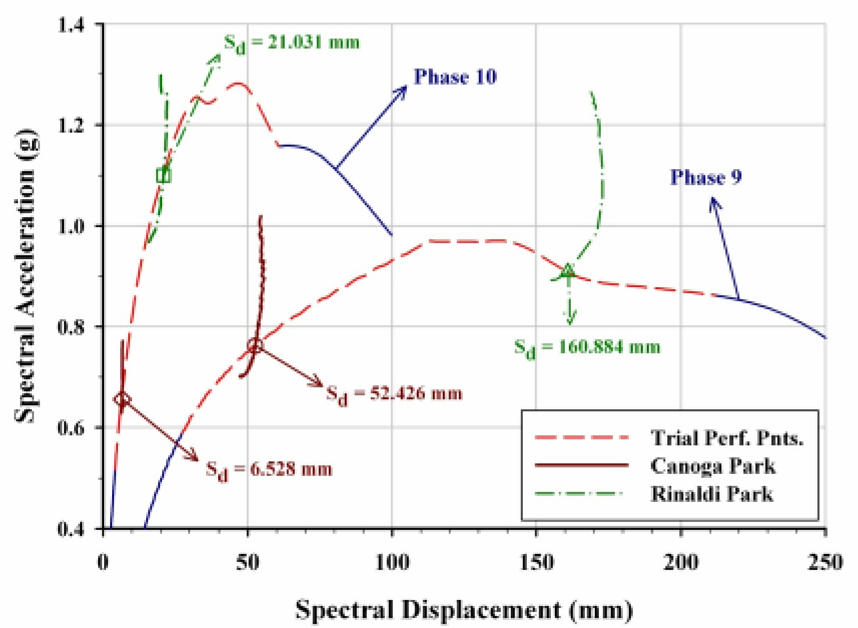
Vulnerability Functions

The EE-1 project has provided an opportunity to integrate the development of structural vulnerability functions in a coordinated effort among researchers from partner universities. In reinforced concrete, fragility functions have been developed for one story tilt-up concrete buildings, four story reinforced concrete frame building, and a five story flat slab building each one having different structural characteristics. The work has included retrofitted buildings and new buildings. In structural steel, parameterized fragility curves for steel-framed buildings have been developed. Fragilities for light-frame wood residential construction that is typical in Memphis area and in general in the Central and Eastern United States are also developed. Another effort has been the development of fragility curves for structures with smart devices, such as active vibration control. This team integrated the MAE Center's advanced analysis package ZEUS-NL with the control toolbox in Matlab through the use of the UI-SIMCOR software, originally developed for substructure testing.

In the area of bridges further work was done in soil-structure interaction to include detailed 3D models for fragility assessment and the liquefaction effects. These fragilities developed for bridges are not only implemented in MAEviz but are also being implemented in REDARS, developed by MCEER.

Advanced Simulation Models

UI-SimCor, a framework for multi-platform distributed simulation has been adopted as the platform of choice by many researchers in the USA, Taiwan, Europe and Japan. UI-SimCor allows the utilization of the best features of disparate analysis package to be integrated, such as OpenSees and Zeus-NL or geo-graphically distributed experimental equipments.



Graphical depiction of results obtained from combining the capacity curve with inelastic dynamic demand points, using the new MAE Center CSM

A new capacity spectrum method (CSM) that addresses the most important shortcomings in existing methods has been derived under this project. The new method was also applied with success to the fragility of wood frame structures reported under EE-1. Figure above shows how the demand curve always intersects the capacity curve, a feature required for successful assessment and one that is not always achieved in currently available methods.

As it approached the end of Year 11, the MAE Center concluded its work on Hazard Definition and Engineering Engines and has focused its attention on wrapping up the social and economic models as well as completing the development of MAEviz cyberenvironment and model implementations. The multidisciplinary nature of the research efforts is further reinforced by the distribution of disciplines shown below.

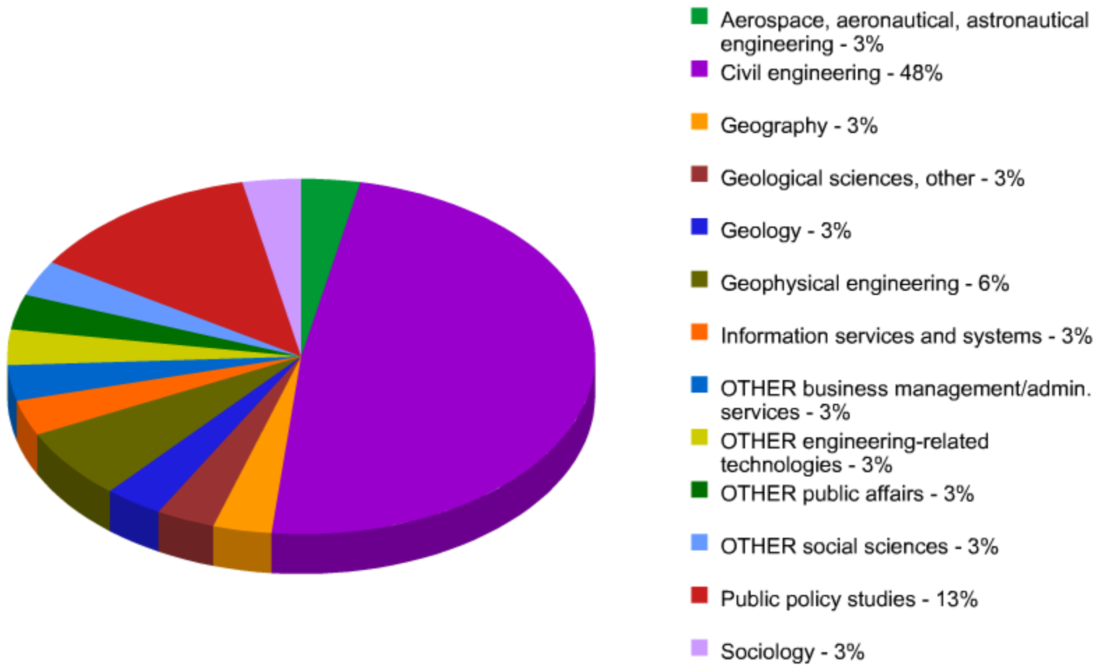
Test Bed Applications in Service of Systems Vision

From the vantage point of its ongoing test bed projects, namely:

- The Regional (Memphis) test bed where all tools are integrated for a site-specific impact assessment on Memphis and Shelby County;
- The Thematic (Transportation) test bed where transportation network models, bridge fragility and functionality are employed to assess the transportation network in Charlestown;
- The Organizational (Emergency Management Agencies) test bed which started in Illinois.

The MAE Center has had the opportunity for a super-integration of all the above—in addition to utilities as well as social and economic impact—in cooperation with its partners at the George Washington University, to undertake the nationally significant New Madrid Seismic Zone Catastrophic Earthquake Response. As a consequence, the

Center has moved to a totally System Plane-based development, implementation and application driven mode to continually improve its regional impact assessment capabilities and provide to the national response planning effort the most reliable assessment results available.



Research Projects by Disciplines

The New Madrid Seismic Zone Catastrophic Earthquake Planning Project provides both an integration medium for all MAE Center products since its inception, and a system-level driver for further development, implementation and application of advanced methods, models and data for regional earthquake risk management.

The MAE Center products that constitute collectively MAEviz have also been utilized by others as stand-alone models, and they therefore constitute important deliverables of the Center. Examples of such components are fragility relationships for buildings and bridges, social impact models, unique data sets for Memphis, Illinois and Istanbul, amongst others.

Impact

The MAE Center approached developing MAEviz both as a conduit for delivering its products and a system-level research prioritization tool. MAEviz is now fully operational as a stat-of-the-art assessment and decision-making web-enabled tool that includes the most up-to-date methods, models and data for earthquake risk management. The components of MAEviz have been utilized by others. Some specific examples are given below:

Laclede Gas and CenterPoint Energy Project

The company is the primary supplier of gas to businesses and homes in the greater St. Louis area and much of its gas network is composed of cast-iron piping. This project will utilize the MAEviz seismic loss estimation and visualization software to estimate the seismic impact from a New Madrid earthquake to Laclede Gas's pipeline network in the greater St. Louis, MO area. Damage and repair estimates will be calculated and visualized using MAEviz. The Center will also utilize the software to determine the performance of the utility network following a significant earthquake event. Interdependencies between the gas utility network and other lifelines such as the power network will also be examined.

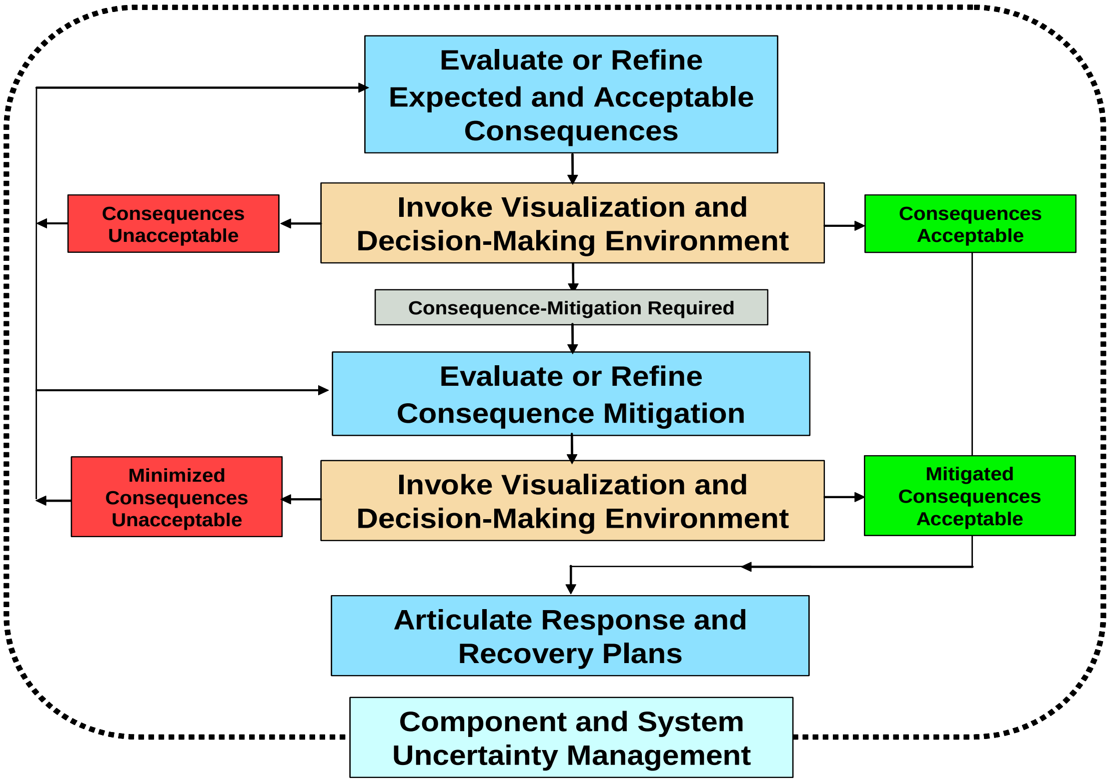
CenterPoint Energy is the main supplier of gas to Laclede. CenterPoint, headquartered in Shreveport, Louisiana, is a natural gas producer and supply company. It provides Laclede with gas via its interstate pipeline system that stretches from Northeast Louisiana north through Arkansas and Missouri to St. Louis. Much of CenterPoint's pipeline network crosses through the New Madrid Seismic Zone so it is at significant risk from a New Madrid earthquake. The loss assessment objectives described above for Laclede will also be conducted for CenterPoint. CenterPoint is co-funding this project with Laclede with the intent of sharing assessment results. The two companies will be provided customized versions of the MAEviz software that will allow them the capability of performing their own seismic risk analysis in the future. The Center will also provide both companies with MAEviz training.

Federal Emergency Management Agency (FEMA) Project

The concept of integrated risk management developed by MAEC is being applied successfully for this FEMA project. The project entails conducting an advanced and comprehensive earthquake loss assessment, response and recovery planning study for the Central and Eastern United States due to a major earthquake from the New Madrid and Wabash Valley Seismic Zones. The study area comprises the states of Alabama, Kentucky, Mississippi, Tennessee, Illinois, Indiana, Arkansas and Missouri. The scope includes regional, state, and city (or town) specific studies at the relevant levels of detail. The Center is partnering with George Washington University's Institute for Crisis, Disaster and Risk Management (ICDRM) on the loss assessment modeling. The scope includes advice on response and recovery planning at all levels, such as local government, industry, aid agencies, and other organizations that are participating in the regional scenario. The project includes augmenting the HAZUS (FEMA's loss estimation software) results with selected analyses for major urban areas and some rural locations using MAEviz. The analysis will also include transportation and utility network flow modeling and decision-support.

Technology Transfer

MAE Center's publications and specifically the web-based application platform -MAEviz that includes visualization, is a state-of-the-art source-to-society impact assessment, and decision-making tool for private industry, State, and Federal officials, and international agencies and organizations. It has already been used internationally for loss assessment. MACE has become the primary source of earthquake information in the Central United States as the nature of ground motion, the probability of major earthquake occurrence is unique to this area as compared to the West Coast of the United States. An application framework for MAEviz is shown below:



Operational Consequence-Based Risk Management

Industry Partnerships

In the last three years before graduation, MAE Center developed business and marketing plans for its sustainability beyond graduation. Three key markets were identified: utility companies; state and federal emergency management agencies; and state departments of transportation, and Federal Highway Administration. An emphasis is placed on marketing the Center's capabilities at modeling seismic loss and the performance of buildings, bridges, and lifelines such as transportation or utility networks using MAEviz. Strategic alliances are developed with consulting engineers, Federal Emergency management Agency (FEMA), State of Illinois Emergency Management Agency and utility companies such as Memphis Light, Gas, and Water and some state transportation departments. MAEC has also some international alliances to utilize MAEviz. The program also coordinates HAZUS loss assessment methodology developed by FEMA with its MAEviz platform.

Education

The Center has been proactive in supporting graduate and undergraduate student involvement in significant, team-oriented and cross-disciplinary research experiences. The Center produced graduates with a multidisciplinary education in loss assessment methodologies and tools. Many graduates were hired by the industry and academic institutions. A continuing center initiative supported opportunities for Practitioner and Student Interaction by providing travel funds for center research assistants to work with government agencies, contractors, or industry personnel on their existing research projects. Several students participated in this program and produced some exciting collaborations, including some new research initiatives.

A graduate course “Consequence–Based Risk Management” is now available as a capstone for presenting the body of knowledge supporting this new technological framework. The course reflects the interdisciplinary nature of earthquake engineering practice and research and provides an overview of diverse topics related to hazard definition, vulnerability assessment, mitigation measures and economic/societal impact.

The MAE Center initiated a project to provide students with international experience to broaden their global perspective through participation in multi-institutional and cross-disciplinary Student Field Missions. This became a tri-center annual event that exposes students, selected through a center-wide competition and accompanied by a center advisor, to a field assessment of the effects of a recent earthquake and to research work in progress at world-class international laboratories.

International Collaborations

MAE Center has signed several Memoranda of Understanding with various organizations and institutions in Korea, Italy, Japan, and Turkey. The MAE Center is an active participant in European Commission’s programs and has played a leading role with the Asia-Pacific Network of Centers of Earthquake Engineering Research (ANCER). Journals and papers co-authored by Center researchers and international researchers, and most recently the Center has been focusing on a reconstructive project for schools in Pakistan & the emerging involvement potential in Indonesia.

The MAE Center is involved internationally working with USAID and independently in providing its expertise in earthquake loss assessment. An example of this is a project to assess the vulnerability of facilities and lifelines in Istanbul, Turkey. In cooperation with Istanbul Technical University (ITU), MAEC has developed, tested and delivered a version of MAEviz for Turkey, referred to as HAZRURK. The software is being used by the Istanbul Municipality for buildings and pipelines. A unique data set of nearly 759,000 buildings with full metadata has been assembled for the region, alongside high-quality data for the utility networks.

Pacific Earthquake Engineering Research Center (PEER) – UC-Berkeley, CA

PEER Center requested a 90-day ‘no-cost’ extension and was granted. The final report was submitted by PEER to NSF on July 11, 2008. At the graduation stage, PEER Center’s key management included Prof. Jack Moehle, Director, Prof. Gregory Deierlein, Deputy Director for Research, Dr. Yousef Bozorgnia, Industrial Liaison Officer, Prof. Scott A. Ashford, Education Program Director, and Ms. Darlene Wright, Administrative Director, along with several thrust leaders. At the graduation stage, PEER Center’s core partner institutions were: *Stanford University; University of California at Irvine; University of California, Davis; University of California, Los Angeles; University of California, San Diego; University of Southern California; University of Washington*; *and California Institute of Technology*. Six academic institutions served as education affiliates, and twenty companies as Business& Industry partners.

Vision

PEER Center's vision is to develop and disseminate performance-based earthquake engineering technology for design and evaluation of buildings, lifelines, and infrastructure to meet the diverse seismic performance objectives of individual stakeholders and society.

Mission

The PEER Center mission is to develop and disseminate procedures and supporting tools and data for performance-based earthquake engineering (PBEE). PEER achieves its mission through research, education, and technology transfer programs aimed at cost-effective reduction of earthquake losses, with emphasis on the following areas:

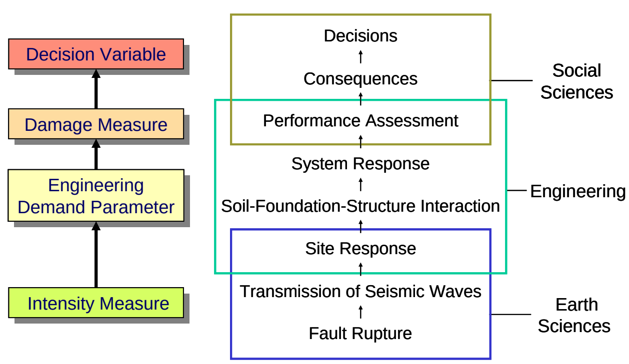
- Definition of seismic hazard for engineering design applications;
- Engineering tools for the seismic assessment and design of constructed facilities, with emphasis on geotechnical structures, buildings, bridges, and lifelines;
- Design criteria to ensure safe and efficient performance of constructed facilities;
- Methodologies including engineering and public policy instruments for mitigating seismic hazards in existing buildings; and
- Performance-based approaches for design and evaluation of constructed facilities to provide appropriate levels of safety for occupants, and protection of economic and functional objectives for essential facilities and operations.

Research Program

PEER Center's research was guided by its overall mission, developed in Year 2, and retained throughout, as stated below:

The PEER mission is to develop, validate, and disseminate performance-based seismic design technologies for facilities and infrastructure to meet the diverse economic and safety needs of owners and society.

To achieve this mission, PEER worked with its Implementation Advisory Board, a group of key industry and government partners, to identify industry needs as well as the products that would be required to meet these needs. A key element to planning the program was development and continual reassessment of the strategic plan. In addition to striving to meet the needs of PEER's stakeholders according to a schedule, the plan achieved a balance among research producing fundamental knowledge, research developing enabling technologies and tools, and research in which the performance-based methodology was tested in proof-of-concept testbeds.

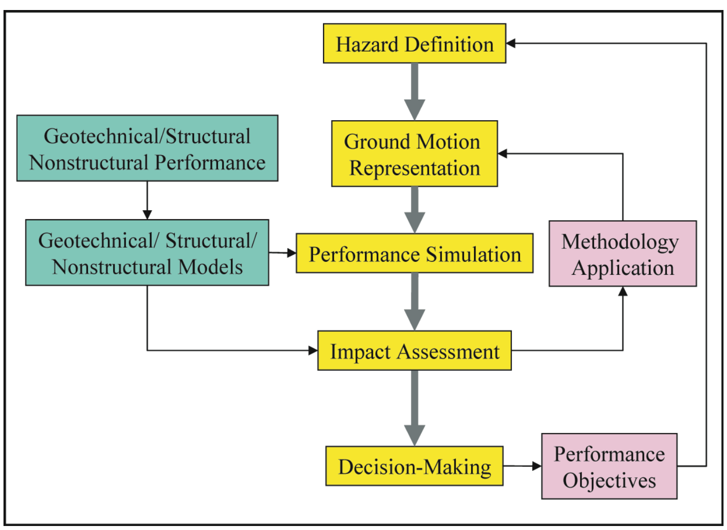


Multidisciplinary Integration in Research Program

Another key element in the research program implementation was evolution of the research thrust areas. In PEER's early years, the research thrusts were organized along disciplinary lines. This organization was a convenient starting point for individuals with similar knowledge base and research culture to work together. Toward PEER's middle years, as the performance-based earthquake engineering methodology was taking form, the research thrust areas were realigned around elements of the methodology, which forced co-mingling of different disciplines. This process was carried further in the past few years by realigning the thrust areas yet again, this time organized around specific constructed facility types so that products could be better directed to the different industries associated with those facility types. In the process, a multidisciplinary research effort as shown above became truly interdisciplinary, with different disciplines working together in support of a common goal. Some key research components are briefly described below:

Performance-based Earthquake Engineering (PBEE)

The approach is aimed at improving decision making about seismic risk by making the choice of performance goals and the trade-offs that they entail apparent to facility owners and society at large. The approach has gained worldwide attention in the past decade with the realization that earthquakes in developed countries impose substantial economic and societal risks above and beyond potential loss of life and injuries. By providing quantitative tools for characterizing and managing these risks, performance-based earthquake engineering serves to address diverse economic and safety needs. There are three levels of decision making that are served by enhanced technologies for performance-based earthquake engineering and that have been focal points for PEER research.

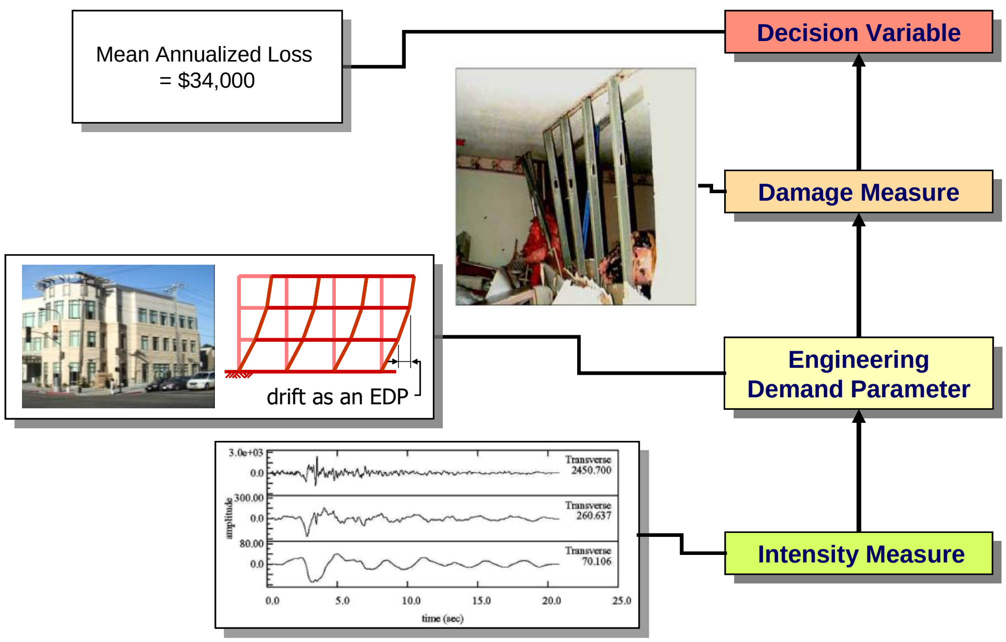


Research elements in PBEE Methodology

One level is that of owners or investors in individual facilities (e.g., a building, a bridge) who face decisions about risk management as influenced by the seismic integrity of a facility. PEER has developed a rigorous PBEE methodology to support informed decision making about seismic design, retrofit, and financial management for individual facilities.

A second level is that of owners, investors, or managers of a portfolio of buildings or facilities—a university or corporate campus, a highway transportation department, or a lifeline organization—for which decisions concern not only individual structures but also priorities among elements of that portfolio. PEER's work shows how to use the rigorous PBEE methodology to support informed decision-making about setting priorities for seismic improvements within such systems by making clear the trade-offs among improved performance of elements of the system.

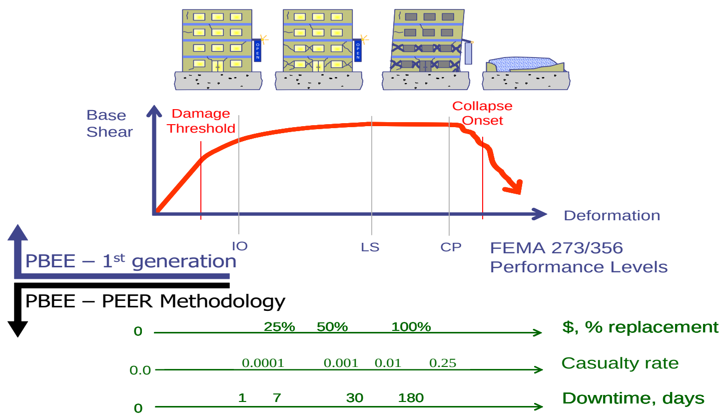
A third level of decision-making is concerned with the societal impacts and regulatory choices relating to minimum performance standards for public and private facilities. PEER's products are being used to support the performance-based development of codes and standards, as well as the performance-based acceptance of specific facilities designed outside the prescriptive provisions of current codes.



Performance–based earthquake engineering framework

***Nonlinear Response Simulation**:*

First-generation PBEE methods relied on either dynamic linear analysis or nonlinear static analysis. The current PEER methodology establishes a rigorous basis to use nonlinear dynamic analyses to simulate structural response from low- response levels up to the point of incipient collapse. These are shown in the figure below. Two key new contributions of this approach are to establish criteria for (a) characterizing ground motions, including the site-specific intensity of the earthquake hazard and the selection/scaling of input ground motions and (b) modeling strength and stiffness degradation, including loss of vertical load carrying capacity.



First and second generation of PBEE methodology

• *Modeling and Propagation of Uncertainties:* Underlying the PEER methodology is a rigorous probabilistic basis that accounts for inherent uncertainties in all aspects of the performance assessment, including uncertainties in (a) the earthquake shaking hazard and site effects, (b) input ground motions, (c) structural modeling parameters, (d) component damage functions, and (e) loss functions.

• *Explicit Damage Measures:* Whereas first-generation PBEE methods primary focus stopped with evaluating engineering demand (response) parameters, the current PBEE methodology provides functions that relate structural demand parameters to the resulting damage to structural and nonstructural components. Associated with descriptions of physical damage to the component(s) are the consequences of the damage, such as the repair measures necessary to restore a component to its pre-earthquake condition or other implications on the damage on facility operation or safety.

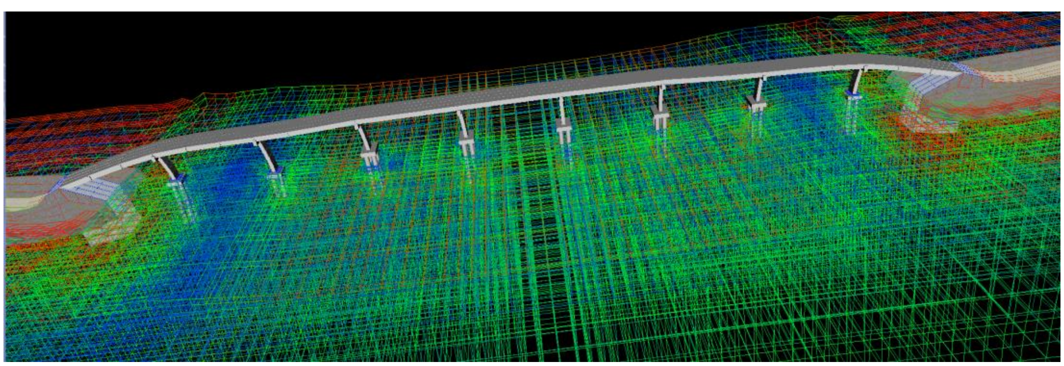
• *System-Level Performance Metrics:* The performance limit states of first-generation PBEE methods (i.e., "immediate occupancy," "life-safety," and "collapse prevention," were somewhat ill-defined and loosely quantified, PEER's PBEE methodology establishes clear metrics that are probabilistically quantified in exact terms that relate to stakeholder decision making. For example, financial losses associated with earthquake repair costs are evaluated in terms of mean annual frequencies, which can be manipulated to inform risk decisions regarding (a) management of risks through mitigation or insurance or (b) scenario-based evaluations to evaluate risk of ruin. Another metric, risk of casualties is a key decision quantity for establishing appropriate minimum safety levels for code requirements.

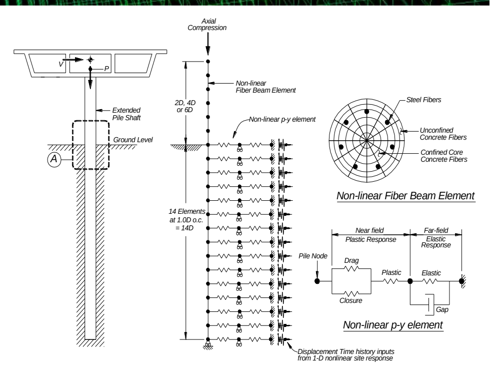
Advanced Simulation Technologies*:*

These technologies are an essential part of PBEE to accurately simulate nonlinear response of buildings, bridges, and other structures, including soil-structure interaction and large ground deformation effects (see Fig). Recognizing the need to integrate state-of-the-art technologies in geotechnical and structural modeling, computational methods, and database technologies, PEER created the computational platform called *OpenSees* (Open System for Earthquake Engineering Simulation). Organized and programmed using an open-source object-oriented approach, *OpenSees* has been an effective platform to implement and test alternative models and solution strategies. *OpenSees* has and is expected to have a major impact on earthquake engineering research. As part of its continued development, PEER also developed a companion platform called *OpenFresco*, which enables hybrid testing and simulation between *OpenSees* and physical experiments.

***Ground Motion Hazard Characterization**:*

A key element of seismic design and analysis in general, and PBEE in particular, is the characterization of earthquake ground motion. PEER has carried out extensive work in this important area. An example of such research projects at PEER is the Next Generation Attenuation (NGA) project. NGA is a comprehensive multidisciplinary research project to characterize ground motions for shallow crustal earthquakes; such as those events in California. The first component of NGA was to compile a database of strong ground motions recorded worldwide. The PEER NGA database is now one of the largest uniformly processed strong-motion databases in the world. The database includes the recorded ground motions, response spectra, and a comprehensive metadata such as earthquake fault mechanisms, various site-to-source distance measures, various shallow site characterization including shear-wave velocity in the top 30-m of soil, among other parameters. The models are also applicable to distance range of 0–200 km from the source, and they include the style of faulting, as well as local soil conditions. The NGA models successfully went through a comprehensive review process carried out by the USGS. The USGS is now adopting the NGA models for generation of the 2007 U.S. National Seismic Hazard Maps. This will affect seismic design of many structures and facilities in the western U.S.





OpenSees model for nonlinear simulation of bridge structure including ground deformations

Impact

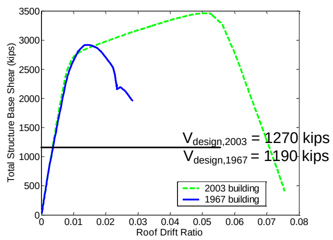
PEER's impacts on engineering science, technology, and practice can broadly be summarized as follows:

(1) establishing a comprehensive methodology framework for PBEE (performance-based earthquake engineering),
(2) development and validation of tools, such as building performance simulation models, to enable the implementation of performance-based methods,
(3) fundamental advancements in knowledge to characterize the seismic performance of buildings, bridges, and lifeline systems and ways to inform risk-management decision making,
(4) implementation of performance-based approaches and tools in engineering practice, and
(5) creating an academic culture of multidisciplinary collaboration that has impacted education and research.

PEER's research has had and will continue to have a considerable effect on engineering practice. Some key examples are noted below. Among the most significant impacts to date are those related to (a) earthquake hazard mapping and real-time assessment, (b) models and criteria to evaluate existing reinforced concrete buildings, (c) models and criteria for evaluation of liquefaction and large ground deformations, (d) analytical tools such as OpenSees for nonlinear analysis, (e) development of performance-based building code requirements, and (f) implementation of PEER's methodology for building loss estimation (ATC 58).

In areas related to earthquake hazards, PEER is collaborating with the USGS on developing new hazard maps that will form the basis of earthquake design requirements for national codes and standards, such as the ASCE 7 *Minimum Design Loads for Buildings and Other Structures.* Specifically, the latest mapping efforts in USGS are utilizing new ground motion attenuation functions developed through PEER research along with research on how to adjust the design ground motions to take into account the effect of spectral shape for extreme ground motions. The net result of this effort will be more accurate and risk-consistent design criteria in high seismic regions of the United States.

2003 Design Codes



Building	Collapse Risk	
	$P_{col.}$/MCE	$MAF_{collapse}$
2003	5%	1 x 10^{-4}
1967	40 to 80%	20 to 50 x 10^{-4}

Impact on Building codes- Benchmarking performance of building systems

PEER's research to characterize the nonlinear collapse performance of older-type (non-ductile) reinforced concrete buildings has markedly improved the tools used in design practice. Through proactive efforts of PEER researchers working with practitioners, PEER research findings have been moved into the recently released standard *ASCE/SEI 41 Seismic Rehabilitation of Existing Buildings* (2007), resulting in numerous substantive changes to the concrete provisions.

Another example of practical impacts of PEER projects is development of a standard set of input motions for shaking table tests for seismic performance evaluation of electric equipment. PEER researchers developed such broadband input motions, and the IEEE Standard 693, a national standard, has adopted the motions for seismic qualification of electric equipment.

Technology Transfer

In addition to the activities described in paragraphs above under 'Impact', PEER has paved the way for collaborative outreach activities, whereby participants from multiple PEER institutions join in technology transfer activities to practicing professionals.

Recent examples include the PEER/EERI seminars on *New Information on the Seismic Performance of Existing Concrete Buildings* (2006), the EERI seminars *Performance-based Earthquake Engineering for Structural and Geotechnical Engineers: Impact of Soil-Structure Interaction on Response of Structures* (2007), the ASCE/SEI 41 Ad Hoc Committee on Updates to ASCE/SEI 41 (2006), the coordinated presentations at the Los Angeles Tall Buildings Structural Design Council Annual Meeting (2007), and others.

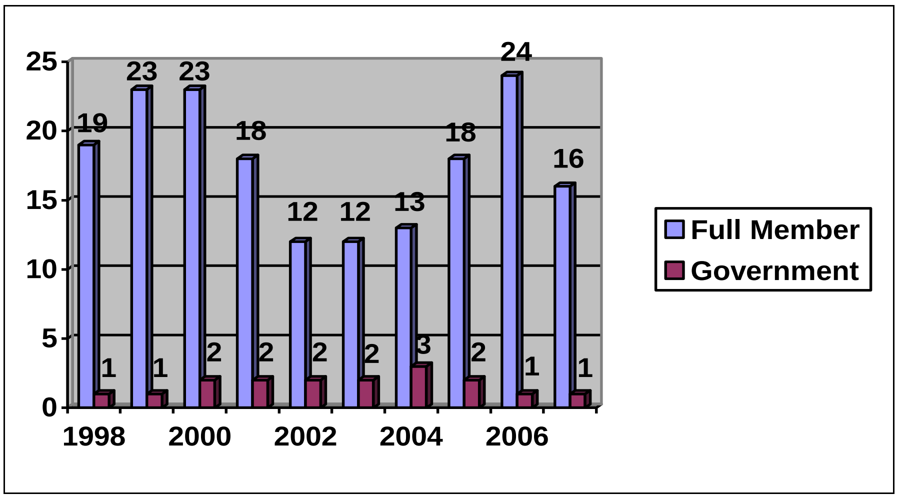
The California Seismic Safety Commission acknowledged PEER Center's efforts in its review and stated:

• PEER is the primary earthquake engineering research arm of the State of California.
• PEER's efforts have produced cost-effective products that benefit the State of California

and are consistent with the goals and initiatives of the California Earthquake Loss Reduction Plan. PEER continues to meet its goals and has been instrumental in affecting State laws and regulations.

Industry Partnerships

The PEER strategy of collaboration is to seek out and engage key players in the government, industry, and business sectors that will be adversely impacted by earthquakes; earthquake professionals with valuable experience in earthquake mitigation that will benefit from enhancing their professional expertise; and organizations with existing earthquake outreach and technology transfer programs that can benefit from technology transfer collaborations with PEER.



PEER members over time

One of the major objectives of the program is to establish sustained government and industry funding to the PEER research program. On the government side, PEER Center has worked continuously with the California Seismic Safety Commission (CSSC) to keep them informed of PEER activities and to keep PEER informed of needs within the State. The CSSC is an important link to the State for the purpose of maintaining the existing State matching funds and for identifying new initiatives that may lead to additional funding. As of graduation date, PEER had 17 industrial members. Most of PEER industrial members fall into the category of consulting firms, as they provide services to the engineering and loss-estimation community. Three of the members, Caltrans, California Energy Commission (CEC), and PG&E, are lifelines organizations providing services to the residents of California for transportation and utilities.

Education

The goals of the PEER Education Program are to introduce, stimulate, cultivate, and educate undergraduate and graduate students with the knowledge that will enable them to contribute to the earthquake-engineering profession from a variety of disciplines and perspectives. The program attracts students to earthquake engineering early in their academic careers and aims to retain them through graduate study.

PEER created a *Summer Internship Program* to attract, train and retain promising undergraduates in earthquake engineering research through a ten-week work under a PEER faculty member. The success of the program lies in the fact that only 15 % decided not to pursue graduate studies. Another program, *Earthquake Engineering Scholars Course* is intended to introduce high-ranking undergraduates to specific topics in earthquake engineering.

The PEER Professional Business and Industry Partners (BIP) Fellows Program is aimed at increasing contacts between our students and practicing professionals by bringing in industry experts for a day of seminars and student-practitioner meetings.

While many courses were modified at the PEER Core and Affiliate Institutions, only two new courses were completely developed and implemented. Both courses were offered at the University of California at Berkeley: CE 227 (Earthquake Resistant Design), in the Department of Civil and Environmental Engineering, and ARCH 259x (Special Topics: Building Structures), by the Department of Architecture.

PEER also offered specific courses to practicing professionals. Examples of courses include PEER Center's presentation at the EERI Technical Seminar Series entitled, "Soil-Structure Interaction for Performance-Based Earthquake Engineering," offered in March 2007 in Seattle, San Francisco, and Los Angeles, and the PEER Workshop on Ground Motion Selection and Modification offered in November 2007 and January 2008 at UC Berkeley.

Several PEER graduates are working in academia mentoring other students in earthquake engineering discipline and interdisciplinary research.

Academic institutions where PEER graduates work

International Collaborations

PEER Center has cooperative projects/programs with several countries in the world where earthquake resistant design of buildings and infrastructure systems is a concern. PEER Center is engaged in collaboration with not only overseas academic institutions, but also with governmental and professional organizations, such as Earthquake Disaster

Mitigation Research Center, Japan, Institute of Engineering Mechanics of China Seismological Bureau, China, and Office of National Science and Technology Program for Hazard Mitigation, Taiwan.

Many technology transfer activities have taken place between the U.S. and these organizations. These technology transfer and international educational programs have helped PEER to ensure the leadership position in Performance –Based Earthquake Engineering nationally and internationally.