Pacific Earthquake Engineering Research Center

an NSF-administered Engineering Research Center
under cooperative agreement number **EEC-9701568**

Core Institutions

University of California, Berkeley ***(Lead Institution)***

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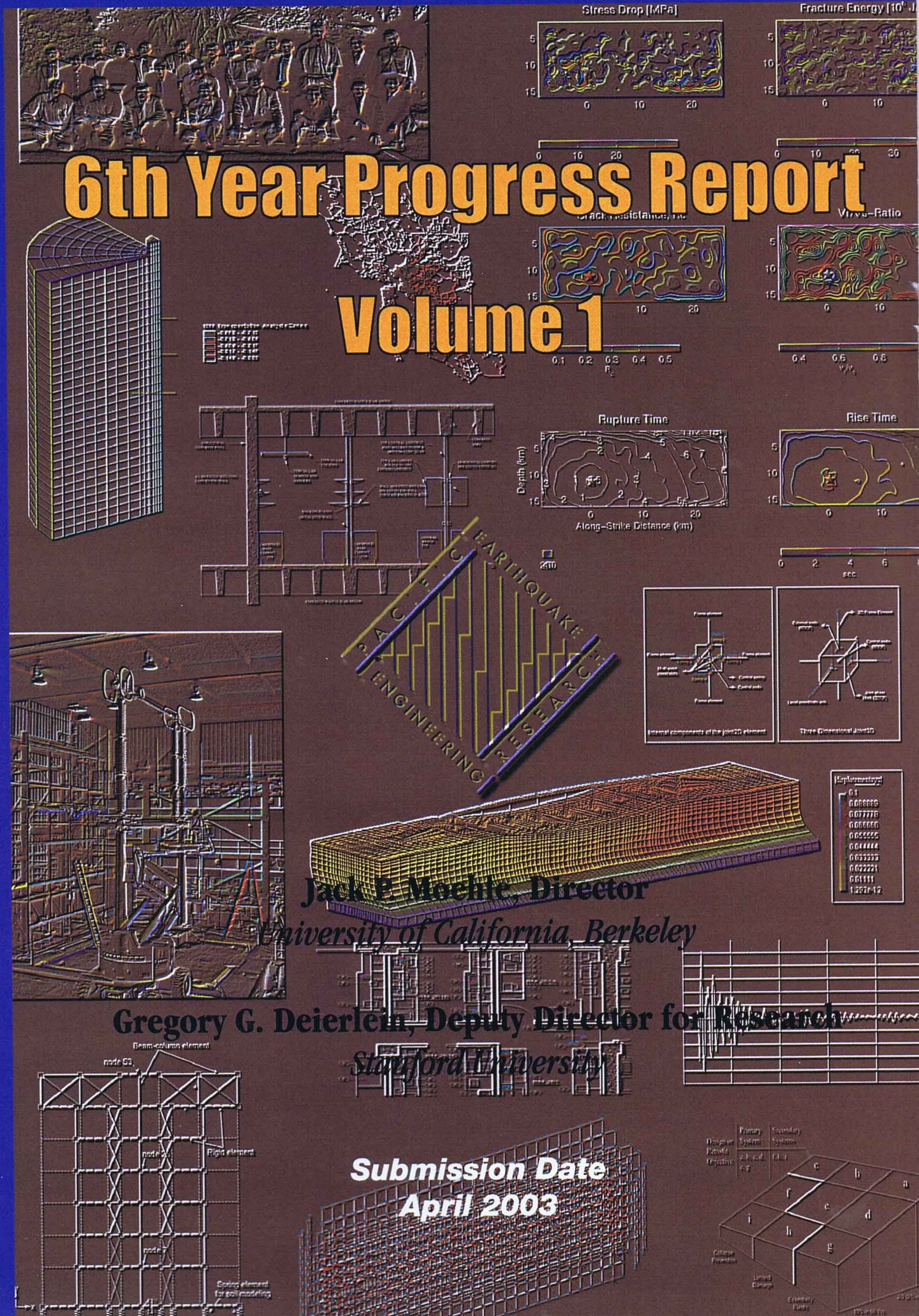

6th Year Progress Report

Volume 1

Jack P. Moehle, Director
University of California, Berkeley

Gregory G. Deierlein, Deputy Director for Research
Stanford University

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PROJECT SUMMARY

The Pacific Earthquake Engineering Research Center (PEER) is an Earthquake Engineering Research Center administered under the National Science Foundation Engineering Research Center Program. The mission of PEER is to develop and disseminate technology for design and construction of buildings and infrastructure to meet the diverse seismic performance needs of owners and society. Current approaches to seismic design are indirect in their use of information on earthquakes, system response to earthquakes, and owner and societal needs. These current approaches produce buildings and infrastructure whose performance is highly variable, and may not meet the needs of owners and society. The PEER program aims to develop a performance-based earthquake engineering approach that can be used to produce systems of predictable and appropriate seismic performance.

To accomplish its mission, PEER has organized a program built around research, education, and technology transfer. The research program merges engineering seismology, engineering, and socio-economic sciences in coordinated studies to develop fundamental data, tools, and methodologies that are tested and refined using testbeds in collaboration with practicing professionals. Primary emphases of the research program at this time are on older and new concrete buildings, bridges and highways, and electric power distribution and transmission systems. The education program promotes engineering awareness in the general public and attracts and trains undergraduate and graduate students to conduct research and implement research findings. The technology transfer program involves practicing earthquake professionals, government agencies, and specific industry sectors in PEER programs to promote implementation of appropriate new technologies. Technology transfer is enhanced through a formal outreach program.

PEER PERSONNEL

Key personnel and participating principal investigators are identified below. Participating principal investigators include those who have received funds in the current reporting period or are scheduled to receive funds in the next period.

KEY PERSONNEL:

Jack Moehle, *Director*, University of California, Berkeley
Gregory Deierlein, *Deputy Director for Research*, Stanford University
Darlene Wright, *Administrative Director*, University of California, Berkeley
Scott Ashford, *Assistant Director for Education Programs*, University of California, San Diego
Michael Riemer, *Lifelines Program Manager*, University of California, Berkeley
Parshaw Vaziri, *Director of Public Relations and Outreach*, University of California, Berkeley
Mary Comerio, *Co–Thrust Area Leader*, University of California, Berkeley
Ahmed Elgamal, *Thrust Area Leader*, University of California, San Diego
Gregory Fenves, *Thrust Area Leader*, University of California, Berkeley
Helmut Krawinkler, *Thrust Area Leader*, Stanford University
Stephen Mahin, *Thrust Area Leader*, University of California, Berkeley
Peter May, *Co–Thrust Area Leader*, University of Washington

FUNDED INVESTIGATORS:

University of California, Berkeley *(Lead)*

Department of Civil & Environmental Engineering

Jack Moehle (Director)
Gregory Fenves (Thrust Leader)
Stephen Mahin (Thrust Leader)
Armen Der Kiureghian
Filip Filippou
Nicos Makris
Khalid Mosalam
Nicolas Sitar
Bozidar Stojadinovic

Department of Architecture

Mary Comerio (Thrust Leader)

Department of Geology & Geophysics

Douglas Dreger

California Institute Of Technology

Division of Applied Science and Civil Engineering

James Beck
John Hall
Keith Porter

Stanford University

Department of Civil and Environmental Engineering

Gregory Deierlein (Deputy Director for Research)
Helmut Krawinkler (Thrust Leader)
Sarah Billington
C. Allin Cornell
Kincho Law
Charles Menun
Eduardo Miranda

Department of Geophysics

Gregory Beroza

University of California, Davis

Department of Civil & Environmental Engineering

Ross Boulanger
Boris Jeremíc
Sashi Kunnath
Bruce Kutter

University of California, Irvine

Department of Civil & Environmental Engineering

Tara Hutchinson
Gerard Pardoen
Roberto Villaverde

University of California, Los Angeles

Department of Civil & Environmental Engineering

Jonathan Stewart
John Wallace

School of Public Health

Kimberly Shoaf

University of California, San Diego

Department Structural Engineering

Scott Ashford (Education Director)
Ahmed Elgamal (Thrust Leader)
Joel Conte
André Filiatrault
José Restrepo
Chia-Ming Uang

University of Southern California

Department of Civil Engineering

Geoffrey Martin
James Moore II
Robert Nigbor

University of Washington

Department of Political Science

Peter May (Thrust Leader)

Business Program

Jacqueline Meszaros
Ufuk Ince

Department of Civil & Environmental Engineering

Pedro Arduino
Marc Eberhard
Steve Kramer
Dawn Lehman
Laura Lowes
John Stanton

Geography Department

Stephanie Chang

AIR Worldwide, Inc.

Paolo Bazzurro
Nicolas Luco

Applied Technology Council

Christopher Rojahn

California Geological Survey

Chris Wills

Comartin-Reis

Evan Reis

Consortium of Organizations for Strong–Motion Observation Systems

J. Carl Stepp

Degenkolb Engineers

Jon Heintz

Geomatrix Consultants

Maurice Power

Imbsen and Associates, Inc.

Roy Imbsen

LAN Engineering

Mohan Char
William Nascimento

OPAC Engineers

Mark Ketchum

Dennis Ostrom

Dennis Ostrom

Pacific Engineering and Analysis

Walter Silva

Rutherford & Chekene

Joe Maffei

San Diego State University

Department of Geological Sciences

Steven Day

San Diego Supercomputer Center
Michael Bailey

United States Geological Survey
David Boore

University of Texas at Austin
Department of Civil Engineering
Kenneth Stokoe II

URS Corporation
Robert Graves
Paul Somerville

PEER EXTERNAL ADVISORY COMMITTEES AND MEMBERS:

Scientific Advisory Committee

Member	Title	Affiliation
Ron Hamburger, *Chair*	*Principal*	Simpson Gumpertz & Heger, Inc.
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Roger Borcherdt	*Engineering Seismologist*	US Geological Survey
Raymond Burby	*Professor*	Univ. of North Carolina, Chapel Hill
James Jirsa	*Professor*	University of Texas at Austin
Tom Jordan	*Professor*	Southern California Earthquake Center
Ronald Mayes	*Staff Consultant*	Simpson Gumpertz & Heger, Inc.

Implementation Advisory Board

Member	Title	Affiliation
James Malley, *Chair*	*Vice President and Senior Principal*	Degenkolb Engineers
Fadel Alameddine	*Senior Bridge Engineer*	California Dept. of Transportation
Robert Bachman	*Consultant*	Private Sector
David Chambers	*Associate Engineering Geologist*	California Energy Commission
Lloyd Cluff	*Manager, Geosciences Dept.*	Pacific Gas & Electric Company
John Hooper	*Director of Earthquake Engineering*	Skilling, Ward, Magnusson, Barkshire
Karl Kirker	*Structural Design Unit Manager*	Washington Dept. of Transportation
Clifford Roblee	*Senior Research Engineer*	California Dept. of Transportation
Christopher Rojahn	*Executive Director*	Applied Technology Council

TABLE OF CONTENTS

APPENDICES

1. SYSTEMS VISION AND BROADER IMPACTS OF THE PEER CENTER

1.1 Systems Vision

> **PEER Mission**
>
> The PEER mission is to develop, validate, and disseminate performance-based seismic design technologies for buildings and infrastructure to meet the diverse economic and safety needs of owners and

The PEER mission is to develop and disseminate technologies to support 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 tradeoffs that they entail apparent to facility owners and society at large. The approach has gained worldwide attention in the past ten years with the realization that urban earthquakes in developed countries – Loma Prieta, Northridge, and Kobe – 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 are focal points for PEER research. One level is that of owners or investors in individual facilities (i.e., a building, a bridge) who face decisions about risk management as influenced by the seismic integrity of a facility. PEER seeks to develop a rigorous PBEE methodology that will 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 seeks to show how to use the rigorous PBEE methodology to support informed decision-making about setting priorities for seismic improvements within such systems by making clear tradeoffs 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 seeks to make technical contributions to development of performance-based codes and standards. The direct beneficiaries of more rigorous approaches to performance-based earthquake engineering are the owners, investors, and risk managers who face these decisions. All of us, of course, ultimately benefit from decisions about seismic risk that better address tradeoffs between the costs of reducing risks and the benefits resulting from seismic improvements.

The clients for PEER advances in PBEE technologies are members of the engineering profession as broadly defined. Performance-based earthquake engineering is bringing about a change in the profession that alters both the role of earthquake engineers (broadening their involvement as consultants for management of earthquake risks) and the demands placed on the profession (changing the methods of risk evaluation, design, and engineering). PEER is working hand-in-hand with business and industry partners to understand how advances in PBEE affect engineering practice and the construction regulatory environment and to identify ways to lessen barriers to adoption and implementation of PBEE. In addition, PEER is very active in educating future generations of earthquake engineers and risk management professionals. As such, PEER seeks to make a major contribution to the development of the earthquake engineering profession.

Despite advances in recent years in the use of performance-based earthquake engineering, existing technologies and methods for PBEE fall short on a number of grounds. Methods for seismic design or evaluation that currently are in widespread use are much less scientific and direct than the rigorous approach that we are developing. Although response of structures to strong ground motions in most cases is expected to be nonlinear, earthquake hazard today is represented by design maps through relatively simplistic single-parameter quantities such as linear spectral response. Likewise, structural evaluation and design commonly use linear analysis adjusted by factors whose values are based on tradition and limited earthquake experience rather than systematic performance considerations. Furthermore, engineering design and assessment generally focus on structural parameters and fail to quantify socio-economic parameters such as direct financial losses, downtime, and casualties. The result of this indirect and empirical approach is that seismic performance outcomes, as demonstrated in recent earthquakes, are highly variable and often at odds with stakeholder expectations.

Seismic design in a technologically advanced society should be more scientifically based. It should provide information on expected seismic performance, measurable in terms that are meaningful to those who must make decisions about performance of facilities, networks or campuses, or the built environment in a broad context. And it should provide options for selecting optimal seismic performance to meet the diverse needs of owners and society.

To meet this objective, we have visualized the implementation of performance-based earthquake engineering as a process involving distinct and logically related steps, illustrated in Figure 1.1. The first step is definition of the seismic hazard, which we have represented by the term *intensity measure*. The second step is determination of *engineering demand parameters* (e.g., deformations, velocities, accelerations) given the seismic input. This leads naturally to definition of *damage measures* such as permanent deformation, toppling of equipment, or cracking or spalling of material in structural components and architectural finishes. Finally, these damage measures lead to quantification of decision variables that relate to casualties, cost, and downtime.

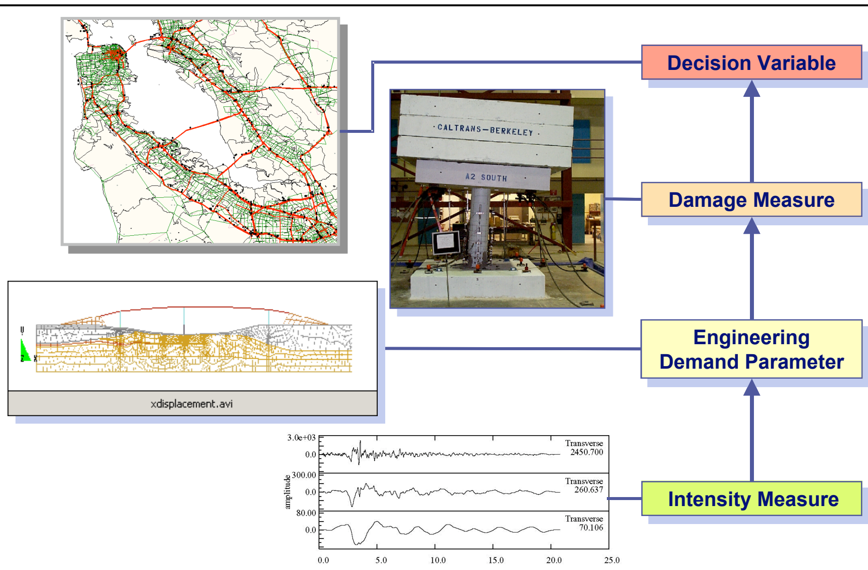


Figure 1.1 – Performance-based earthquake engineering framework. PEER is conducting research on individual elements and the overall framework. Images from some PEER projects are shown left.

An essential element of performance-based earthquake engineering is the integration of issues across disciplinary boundaries, as illustrated qualitatively in Figure 1.2. The central column of the figure suggests various steps that might be involved in a performance assessment of a system for a single earthquake event. The left side of the figure shows discrete variables that PEER has defined as part of its framework for performance-based earthquake engineering. The right side of the figure identifies the traditional disciplinary contributions to the problem. The solution of the earthquake problem clearly is a multi-disciplinary endeavor.

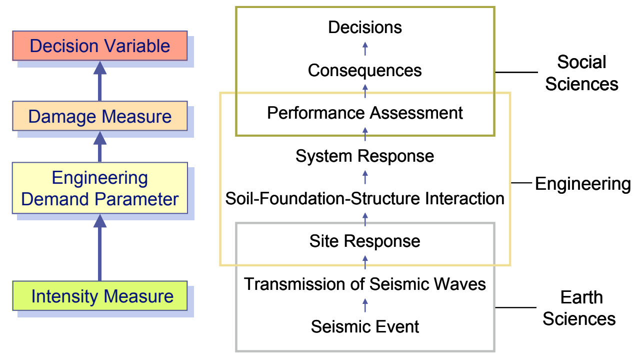


Figure 1.2 – Multi-disciplinary integration in performance-based earthquake engineering. Steps in performance-based earthquake engineering shown center, PEER's framework variables shown left, and traditional disciplines shown right.

The PEER programs in research, education, industry partnerships, and outreach are geared to producing the technology and human resources necessary to transition from current design and assessment methods to performance-based methods. The primary goal is to produce and test through research the fundamental information and enabling technologies required for performance-based earthquake engineering. The Education Program promotes earthquake engineering awareness in the general public, and attracts and trains undergraduate and graduate students to conduct research and to implement research findings developed in the PEER program. The Business and Industry Partner Program involves earthquake professionals, relevant industry, and earthquake information users in PEER activities to ensure the utility of the research and to speed its implementation. The Outreach Program presents the PEER activities and products to a broad audience including students, researchers, industry, and the general public.

Ultimately, a PEER objective is to facilitate the development of practical guidelines and code provisions that will formalize performance-based earthquake engineering in practice, replacing some of the first-generation documents on this approach [e.g., FEMA 273, ATC 32, ATC 40, FEMA 354]. PEER is working closely with other organizations, including the Applied Technology Council and the Federal Emergency Management Agency, to develop and implement methodology that will form the basis of next-generation performance-based guidelines. Additionally, PEER produces models and data that are useful, useable, and used in industry. The process is aided by the involvement of practicing earthquake professionals in our program, who help guide and incorporate our research advances as they occur. As a result, the PEER program is an important contributor to national, state, and local efforts to reduce earthquake hazards that threaten the interests of the government, industry, and the general public.

1.2 Value Added and Broader Impacts

PEER provides the opportunity for focused, long-term study to advance performance-based earthquake engineering. Although the basic concepts of performance-based earthquake engineering have existed previously, there has not been an opportunity to examine the performance metrics, the underpinning technologies, and the overall framework for implementation in professional practice. Examination of these broad issues requires a multi-disciplinary effort involving earth scientists, engineers, social scientists, and experts from other related disciplines. It also requires development of a framework that can link the different parts of the problem (seismic hazard, engineering demand analysis, performance assessment, and decision-making), consistently and systemically incorporating the uncertainties so that an overall statement on reliability can be made. Finally, it requires a longer-range vision so that the final methodology is not just an improvement in current methods but instead makes the major step in information and technology advancement necessary for realistic implementation of performance-based earthquake engineering. PEER is providing the focus, resources, vision, and professional and educational environment that make these things possible.

Participation in PEER has resulted in a genuine transformation in attitudes and outlook among PEER researchers and participants who recognize and embrace the broader perspective that PEER promotes. The collaborative spirit and activities inspire creative thinking that one researcher or research group could not achieve in isolation. This is producing unique accomplishments in new areas with outcomes that impact the overall research direction.

One of the major accomplishments in the past year has been the evolution in thinking about quantification of damage and other decision variables. This evolution is primarily a result of multidisciplinary work on the PEER methodology testbeds. The testbeds were introduced in Year 5 as a means of testing the PEER methodology on real structures and networks, identifying methodology and data gaps, and improving participation of PEER's industry partners. The testbeds have significantly improved integration of the different aspects (and disciplines) of the performance-based earthquake engineering problem, and have helped focus attention on modeling, simulation, and data gaps which require additional development in Year 7.

Another area of significant growth is in collaborations with other earthquake centers in the U.S. PEER previously has collaborated on a relatively limited basis with the Southern California Earthquake Center and the other two Earthquake Engineering Research Centers – the Mid-America Earthquake Center and the Multidisciplinary Center for Earthquake Engineering Research. During Year 6, we have embarked on joint strategic planning that already has led to joint funding of several projects that provide important leverage and synergy.

PEER also has made several specific accomplishments in the broad categories of *People*, *Ideas*, and *Tools*, as summarized below:

<u>PEOPLE:</u>

PEER Research Experience for Teachers Program identifies science and earthquake engineering opportunities for teachers and K-12 students.

Middle school students and teachers gain experiences in science and earthquake engineering through PEER's Research Experience for Teachers program

Middle school students from the inner city are often unaware of career opportunities in science and engineering. In an effort to improve math and science education at the middle-school level, PEER has begun working with teachers and their students through a NSF-funded Research Experience for Teachers (RET) supplemental grant. Our goal is to increase the knowledge and skill level of teachers from inner city schools, while at the same time having some direct impact on their students. All these efforts revolve around earthquake engineering. Nine teachers from eight inner-city schools spent several weekends on a PEER campus learning about earthquake engineering from faculty and graduate students, as well as receiving detailed instruction on operation of the university's laboratory equipment. These teachers then worked with their own students to develop science fair projects with experiments carried out by the students and teachers at the PEER university campus. Two of these projects have made it to countywide science fair finals. We're making an impact on K-12 education in two ways: (1) by developing earthquake engineering knowledge and laboratory skills of the K-12 teachers that they can utilize in the classroom, and (2) by exposing K-12 students to the university environment so that they can begin to realize it is an achievable goal for them.

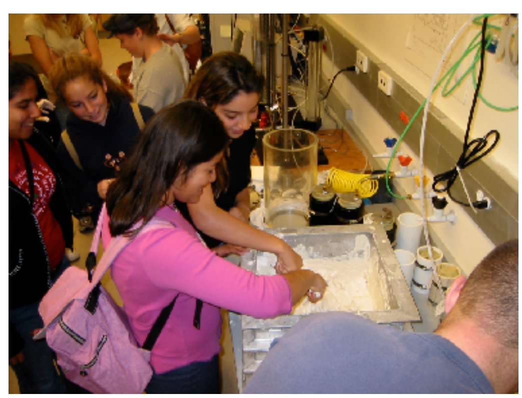
Summer Intern Program provides opportunities for research and professional interaction

PEER's *Summer Internship Program* is designed to attract, train, and retain promising undergraduates who have expressed an interest in earthquake education and earthquake-related fields. In 2002, 15 students were accepted into the program. Each intern worked under the direction of a PEER faculty member on a PEER-funded project. The students were required to work 400 hours and submit a final report in order to receive their full summer stipend. For the past three years, these PEER students have also participated in a special poster session at the Earthquake Engineering Research Institute Annual Meeting, this year held in Portland, Oregon. For many of these students, the summer experience is their first exposure to research, and the EERI meeting is their closest contact with practitioners.

PEER Summer Interns present their research to practitioners at the 2003 Earthquake Engineering Research Institute Annual Meeting.

Educational Shake Tables attract K-12 students to PEER

The Tri-Center "Instructional Earthquake Simulations" Project is aimed at increasing students' knowledge of earthquake engineering through the use of small earthquake simulators specifically designed for use in a classroom setting. Shaking tables have generally been used more as research tools than as instructional devices. To encourage more interest in structural



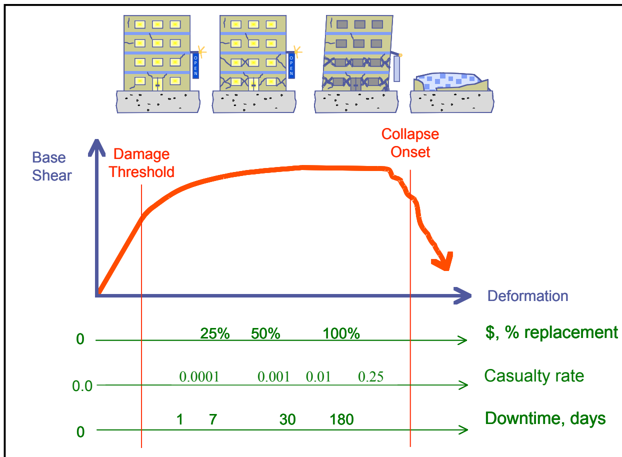
Middle school students preparing sample for testing.

dynamics and earthquake hazard mitigation at the undergraduate level, 23 institutions drawn from the three national earthquake centers cooperated in the design of a bench-scale shake table; presently, the number of participating institutions has grown to 40 and created a consortium known as UCIST (University Consortium of Instructional Shaking Tables). The equipment is used to integrate earthquake engineering into the undergraduate curriculum. Classroom demonstrations and "hands-on" experiments are conducted at all levels in order to have a significant impact on the curriculum. In addition, the shake tables are displayed and demonstrated at public awareness events including: state fairs, primary and secondary schools, and local community disaster preparedness programs.

IDEAS:

PEER's methodology framework for performance-based earthquake engineering gains broader acceptance

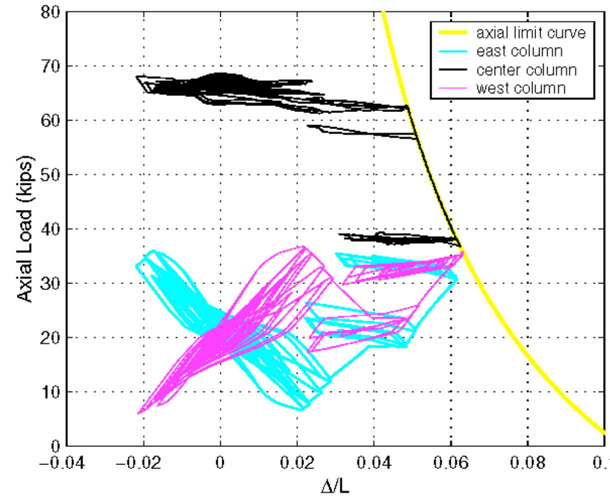
PEER's methodology framework for performance-based earthquake engineering serves as foundation for major initiatives in earthquake engineering PEER has established a comprehensive framework to integrate multi-disciplinary aspects of earthquake performance assessment. Underlying the methodology is an emphasis on utilizing state-of-the-art computational and information technologies to simulate building and bridge response to extreme loading events, as well as a commitment to quantify performance using metrics that are relevant to decision-makers. Since its inception, the framework has been an effective means to plan and coordinate research in PEER. The framework is now gaining acceptance outside PEER in the broader earthquake engineering research and practice community. In one example, PEER's performance assessment methodology has been adopted as the basis for a new FEMA-funded project (organized as Applied Technology Council Project No. 58) to develop national consensus standards for performance-based earthquake engineering. Furthermore, leading PEER researchers and industry partners are helping direct the vision for the ATC 58 project through service on the management, steering, and task committees. In another example, leading PEER researchers and industry partners were engaged by the Bay Area Rapid Transit (BART) district to help develop its risk management plan using the performance-based earthquake engineering framework. Through these and other examples, PEER's framework for performance-based earthquake engineering is finding real-life testbeds to examine the detailed workings of the framework and, in the process, changing the way earthquake engineering is being practiced.



PEER's performance-based earthquake engineering methodology quantifies decision variables such as casualties, cost, and functionality as an aid to decision-making

Models and simulation procedures to identify collapse-potential in existing buildings

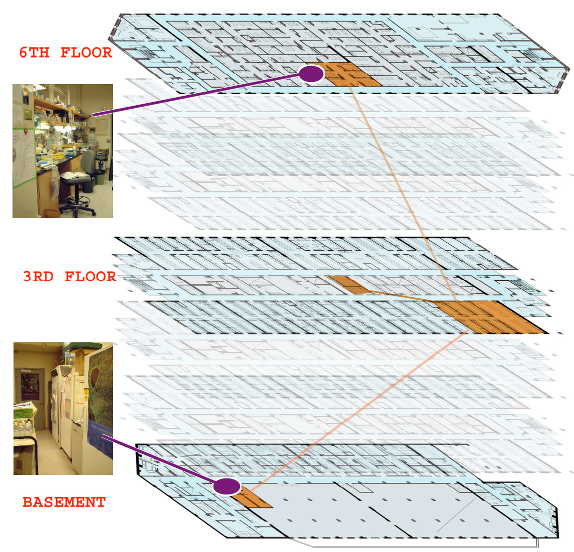
A major challenge in structural engineering is assessment of the safety of older existing buildings that may be susceptible to massive collapse during strong earthquakes. Analysis tools available to the engineering community previously have been unable to model this highly nonlinear dynamic problem. PEER research has expanded the capability to model the process of building collapse so that engineers can make more informed assessments of collapse potential. In a series of carefully conducted static and dynamic tests (http://peer.berkeley.edu/%7Eelwood/research/), PEER has monitored and classified the critical mechanisms of column failure that lead to building collapse. The phenomena have been incorporated in a new analytical model implemented within PEER's framework for nonlinear dynamic analysis, OpenSees. The new capability enables engineers to study the collapse problem and better identify those buildings that are susceptible to life-threatening collapse. This will lead to more economical and safe seismic retrofit of the existing building stock.



Response of a simple, three-column building frame. The yellow curve is the axial failure envelope while the other curves are computed relations between column axial force and lateral displacement. As different columns intersect the interaction surface, axial load is shed to adjacent columns, driving them toward the interaction surface and eventual frame collapse.

PEER partners with university officials and engineers to develop disaster-resistant campus

Situated astride the seismically active Hayward fault, the University of California's Berkeley campus provides a real-life testbed for performance-based earthquake engineering methods under development by PEER. Working closely with professional engineering consultants



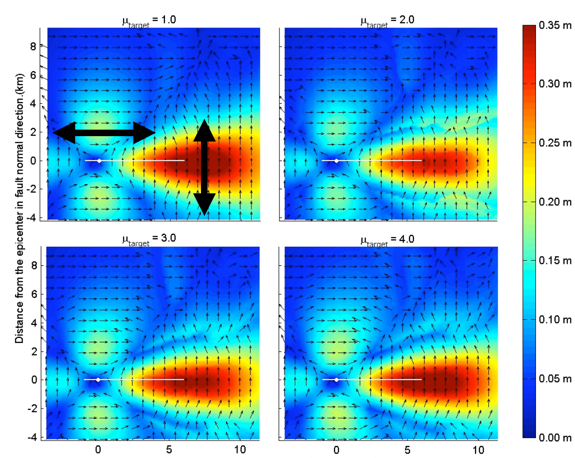
GIS-based models of a campus laboratory building are used to understand the functional and special relations among different components of a laboratory so that the impacts of component performance on system-level functionality can be established.

and university administrators, PEER researchers are providing campus administration with tools to assess campus risk; develop retrofit/mitigation strategies; and conduct disaster planning. This work is being coordinated with a FEMA supported Disaster Resistant University initiative, whose aim is to develop a model that other university and industrial campuses can follow. This initiative began with a detailed assessment of the earthquake risk on the Berkeley campus, which identified substantial risks that are concentrated in a small percentage of the campus buildings. This led to subsequent and more detailed study of a life-sciences laboratory to assess the seismic performance of the building itself as well as the valuable contents of the building. Shake table tests of critical laboratory equipment are providing data to develop cost-effective strategies to reduce damage, losses, and life-safety hazards. Joint efforts on the campus study have also involved testing of structural and foundation elements for buildings to develop more cost-effective designs for new construction and retrofit to existing buildings. This work is attracting widespread interest from decision-makers at other universities, industrial facilities, and museums, who recognize the importance of cost-effective seismic protection for buildings and their contents.

TOOLS:

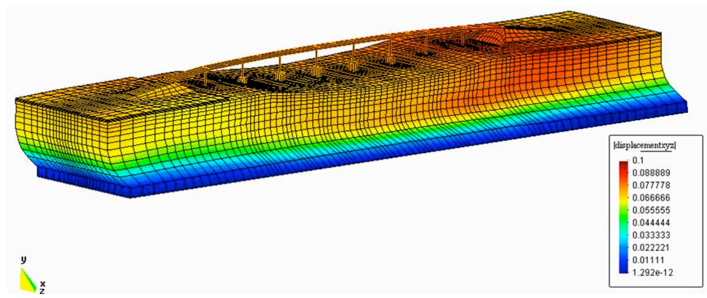
OpenSees — the Open System for Earthquake Engineering Simulation

A centerpiece of PEER's mission of performance-based earthquake engineering is new research on simulation models and computational methods to assess the performance of structural and geotechnical systems. Breaking the barriers of traditional methods and software development protocols, PEER has embarked on a completely new approach in the earthquake engineering community by developing an open-source, object-oriented software framework. *OpenSees* is a collection of modules to facilitate the implementation of models and simulation procedures for structural and geotechnical earthquake engineering. By shared development using well-designed software interfaces, the open-source approach has effected collaboration among a substantial community of developers and users within and outside of PEER. Unique among software for earthquake engineering, *OpenSees* allows integration of models of structures and soils to investigate challenging problems in soil-structure-foundation interaction. In addition to improved models for reinforced concrete structures, shallow and deep



OpenSees is used to simulate the nonlinear response of simple structures located at 25,000 points on a 10x10 km region subjected to a M=6 strike-slip fault. The contour plots show the maximum displacement of structures with a 1 second vibration period and different ductility levels. The strike-slip produces regions in which fault normal response is dominant and other, smaller regions, in which fault parallel response is dominant.

foundations, and liquefiable soils, *OpenSees* is designed to take advantage of the latest developments in databases, reliability methods, scientific visualization, and high-end computing. PEER has provided substantial support to the community by sponsoring three workshops on *OpenSees*, attended by more than 100 researchers and engineers. Over 300 developers and users share insights and are kept appraised of the latest developments through on-line collaboration tools. The *OpenSees* website http://opensees.berkeley.edu provides the source code, documentation, examples, user group links, and information about the development roadmap for the software.

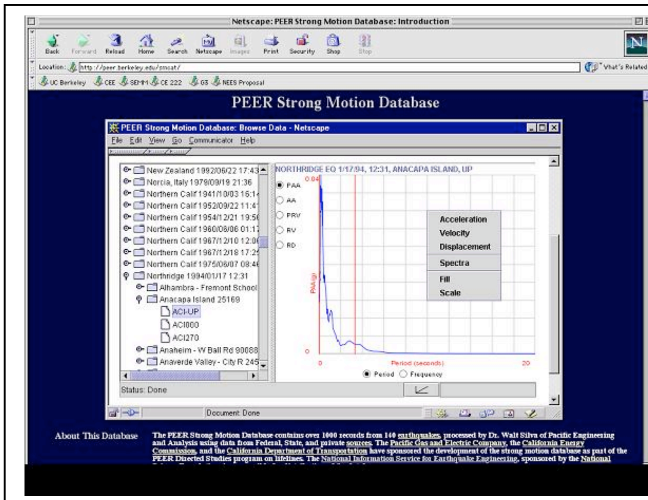


The OpenSees model of Humboldt Bay Bridge of the bridge, foundations, and soils is used to study the effect of soil liquefaction and permanent displacements on the performance of the bridge in an earthquake.

OpenSees will provide excellent opportunities for numerical simulation in the context of NEES. OpenSees is advocated by the NEES System Integration team as one of the community developed simulation platforms for which portals will be developed for integration with the NEESgrid system. This could greatly expand the user community for OpenSees and encourage further development of programs that can be merged into the OpenSees platform.

PEER Strong Motion Database expansions contribute to next-generation attenuation relations

Current methods for predicting likely ground shaking at a given site rely heavily on careful interpretation of the available empirical data from past earthquakes. When data are compiled into conventional attenuation relationships, the large degree of scatter leads to substantial uncertainty in the predicted motions. The PEER Strong Motion Database has been compiled to bring together over 1,500 records from 143 different earthquakes in a web-accessible format. Current developments for the database are expanding it by introducing more records and improving the information about the records. In conjunction with multiple other PEER projects, the database is including more detailed and

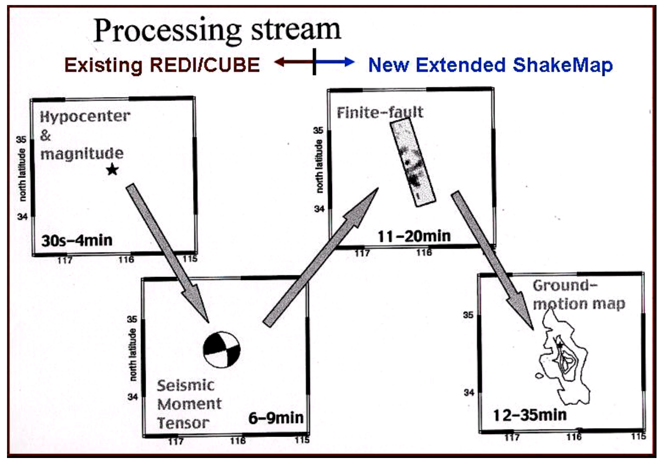


PEER's Strong Motion Database enables engineers and model developers to assemble suites of representative strong ground motions for earthquake engineering applications and model development

accurate characterization of the site conditions at many of the important strong motion stations, and the details of the rupture mechanism. The new information is fostering the development of next-generation attenuation models that are more sophisticated and that reduce the uncertainties in predictions of the expected levels of shaking.

Rapid estimation of earthquake ground motions for emergency response and lifeline operators

Immediately after a major earthquake, emergency responders and operators of lifeline systems in the affected area need guidance as to the likely distribution of damage. In areas that are densely instrumented with a network of seismometers, the measured distribution of strong ground shaking can be rapidly assembled and broadcast as an indirect measure of likely damage. In sparsely instrumented locations, however, insufficient empirical data may be available. To supplement such data, new methods make it possible to automatically determine finite-source parameters of earthquakes such as the causative fault plane characteristics and rupture velocity. These source parameters are then used to simulate near-fault ground motions for areas where there are no nearby recording instruments. This process can be carried out automatically, to produce and distribute estimates of shaking within 30 minutes of the event, and can then be reviewed and updated by seismologists in real time. The process is aided by previous PEER studies aimed at improving simulation technologies. This is an important contribution toward the objective of near-real-time reporting of earthquake shaking hazard, and has been provided to ShakeMap V2.x software for widespread application.



Existing Shake Map capabilities enable maps of strong ground shaking to be developed in the minutes following an earthquake, but only in areas with dense ground motion instrumentation. PEER research has extended the capability using simulation to fill gaps in sparsely instrumented regions.

1.3 NSF Engineering Research Center Quantifiable Outputs and Benchmarking

The National Science Foundation Engineering Research Centers (ERC) Program has established fixed parameters for measuring the outputs of ERCs. These are summarized in Table 1. PEER emphasizes quantifiable outputs such as publications and data, tools, and methods implemented in professional practice, with reduced emphasis on licenses, patents, and spin-off companies. More information on PEER products can be found at http://peer.berkeley.edu.

2. STRATEGIC RESEARCH PLAN

This section describes the PEER strategic research plan and provides summary information on its research program, including information on research outreach and detailed thrust-level information. Additional details on individual projects are in Volume II.

2.1 PEER Strategic Research Plan

The PEER mission is to develop, validate, and disseminate performance-based earthquake engineering (PBEE) technologies for buildings and infrastructure to meet the diverse economic and safety needs of owners and society. Although some methodologies already exist (e.g., FEMA 273 and 356 for performance-based building evaluation and HAZUS for regional loss estimation), these procedures are largely unverified and lack necessary capabilities. PEER aims to enhance existing thinking on performance-based earthquake engineering and to respond to needs and requirements of various stakeholders by providing products and outcomes that are of broad impact and utility.

The PEER research program for developing earthquake engineering is guided by a strategic research plan and organized around five thrust areas. The plan is illustrated by a series of graphics that display the integration of various disciplines, projects, and products, and ensure balance among research aimed at producing fundamental knowledge, enabling technologies, and systems-level methodology development and implementation. An overview of the systems-level research plan is described in this section, followed by details on specific milestones, research organization, and thrust-area specific plans in subsequent sections.

Figure 2.1 illustrates the systems-level research plan. The plan is driven by *Needs and Requirements of Clients, Stakeholders, and the Marketplace*; involves research within *Technology Integration*, *Enabling Technologies*, and *Knowledge Base Planes*; and produces *Products and Outcomes* that respond to the *Needs and Requirements*. The following subsections describe each of the main elements of Figure 2.1.

2.1.1 Needs and Requirements of Clients, Stakeholders, and the Marketplace

As discussed in Chapter 1, three levels of decisions are served by enhanced technologies for PBEE. These define the *Needs and Requirements* (Figure 2.1) for PEER research:

- One level of decision is that of designers, owners, or investors in individual facilities (i.e., a building, a bridge) who face decisions about the seismic integrity of that facility and the management of risk that it poses. PEER seeks to develop a rigorous PBEE methodology that will inform decisions 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 not only concern individual structures but priorities among elements of that portfolio (as well as the behavior of the network in the case of lifelines). PEER seeks to show how to use the rigorous PBEE methodology to inform decisions about setting priorities for seismic improvements within such systems by making clear tradeoffs among improved performance of elements of the system.

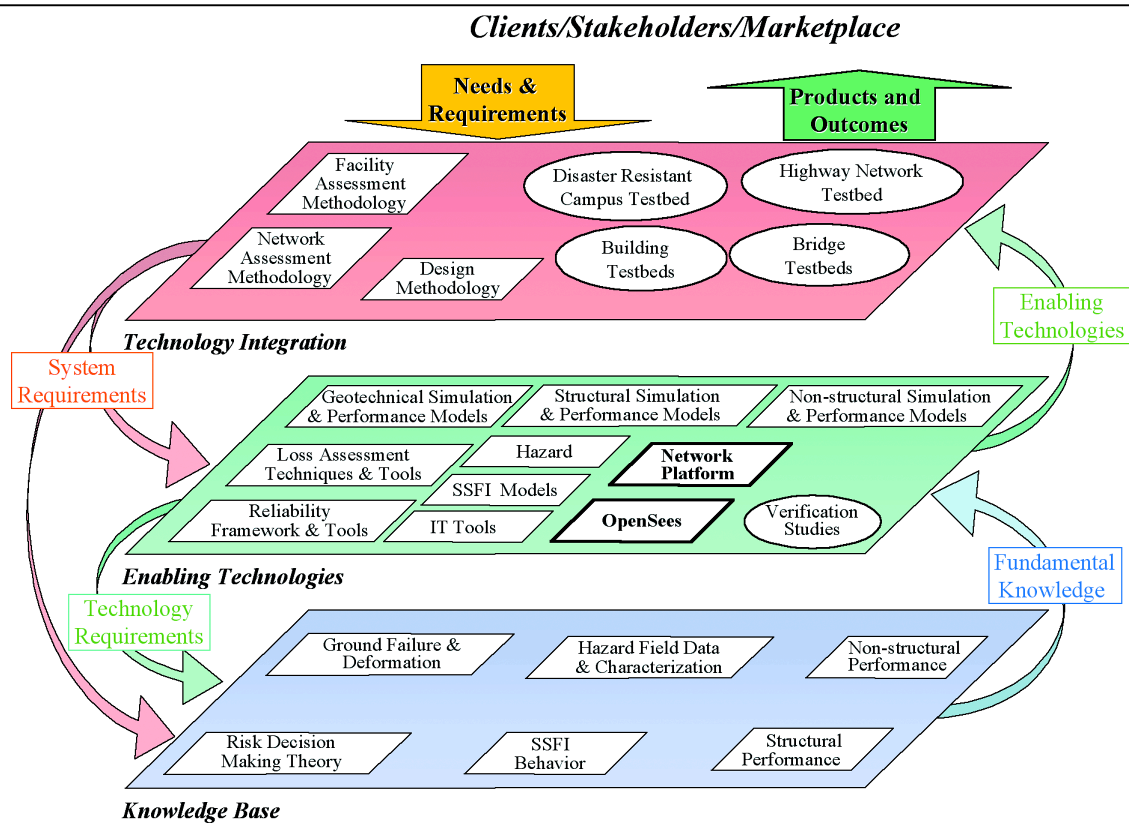


Figure 2.1 - Systems Level Strategic Plan

- A third level of decisions is consideration of the societal impacts and regulatory choices relating to minimum performance standards for public and private facilities. PEER seeks to make technical contributions to development of performance-based codes and standards.

It is our view that a unified approach to characterize performance can be developed to satisfy each of these types of decisions. To achieve this approach, a more fundamental definition of performance is required than has been used in the past. This unified approach aims to characterize performance in terms of probabilities of exceeding a specified loss during a specified exposure period. This differs from the current approach for seismic design or assessment of individual facilities, which aims somewhat arbitrarily for specific performance levels associated with specific hazard levels.

A conceptual illustration of the approach we envision is shown in Figure 2.2. The upper portion of the curve illustrates the load-displacement envelope for an individual facility such as a bridge or building. Two readily defined points on the curve correspond to the linear-elastic and collapse limit states. One performance-based design procedure in widespread use for seismic rehabilitation of existing buildings, FEMA 273/356, defines three performance levels, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Each of these performance levels is based on the individual component that has the worst performance, that is, as soon as one component reaches the LS state, the entire building is assumed to be at the LS state. The component-based limit states themselves were based considerably on judgment and have been the subject of continuing debate and discontent. The individual performance levels are paired with hazard levels (e.g., probability that the ground motion will exceed a certain level in a fixed period of time) without any calibration to determine if the results are optimal.

The PEER vision is to advance the state-of-the-art and the state-of-the-practice of PBEE by numerically tying performance to the losses of interest. As identified in Fig. 2.2, the losses of interest are direct dollar loss, casualty loss, and loss of function. Notably, these are applicable to individual facility design and assessment, facility rating systems, portfolio analyses, and regional loss studies, and thereby provide a unifying means of assessing performance for the range of needs and requirements of the clients, stakeholders, and marketplace for PBEE.

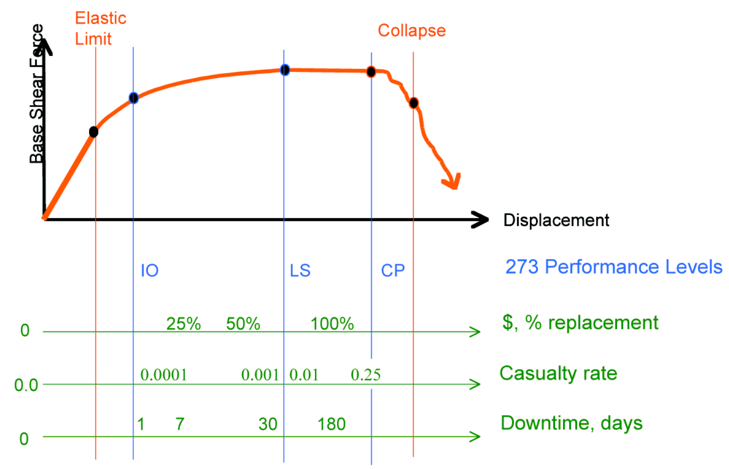


Figure 2.2 – Idealized relation between performance and load-deformation response (after Holmes, PEER 2001 Annual Meeting)

PEER's research focus is toward developing an accepted "performance engine" or "means of verification" to evaluate the performance metrics (dollar losses, downtime, and casualty rates) and, thereby, fulfill the promise of PBEE. In our view, PBEE must embrace the next generation of computational and modeling procedures, must explicitly represent randomness and uncertainty, and must model the seismic hazard, the site, the structure, the nonstructural elements and systems, and the socio-economic impacts. Furthermore, it should take advantage of complete dynamic simulation where practicable, while providing guidance for simplified representations such as the inelastic load-displacement envelope (pushover curve) of Figure 2.2.

The conceptual elements of PEER's "performance engine" and their interrelations are shown in Figure 2.3. This chart, and its relationship to the systems-level strategic plan (Fig. 2.1), is described in detail in the following sections.

2.1.2 Technology Integration Plane

The Technology Integration Plane of Figure 2.1 represents the systems-level applications and studies in PBEE. For an individual facility, the system includes the seismic environment; the soil-foundation-structure-nonstructural-contents system; and the facility-impacted stakeholder segments. For a network of facilities as in a lifeline network, the system includes the seismic environment; the individual facilities and their linkages; and the impacted regional stakeholder segments.

The Technology Integration Plane contains the primary long-range objectives of the PEER research program – specifically, the development of assessment and design methodologies that integrate the seismic-tectonic, infrastructure, and socio-economic components of earthquake engineering into a system that can be analyzed and on which rational decisions can be made. These methodologies should be applicable to individual facilities and to inventories of interacting facilities. Testbeds are established to exercise the methodologies, identify additional needed research, lead to simplified approaches, and demonstrate the socio-economic impact of different performance objective formulations.

2.1.2.1 Methodology Description.

The assessment methodologies under development need to span from the seismic hazard through to impact assessment. The fundamental process involved in the methodologies is depicted in Figure 2.3. The specific steps in the process are as follows (the global process is described for an individual facility, but is essentially the same for distributed networks):

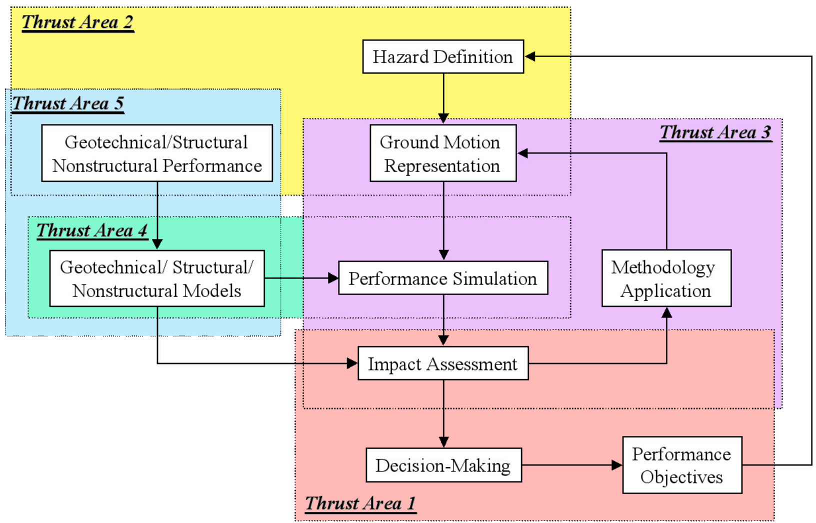


Figure 2.3 – Research elements in the performance-based earthquake engineering methodology and the relation to Thrust Areas.

- *Hazard Definition* – The seismic hazard environment is defined by identification of active faults affecting the site and a probabilistic statement of the occurrence of different magnitude and mechanism events as a function of time and space.
- *Ground Motion Representation* – This step is to identify and quantify (in a statistically acceptable way) assessment/design ground motions for the site considering the hazard, attenuation of critical ground motion parameters, and site characteristics (to the extent that the site and its effect on ground motions is considered external to the facility). In an engineering implementation, other ground motion representations such as response spectra may be used.
- *Geotechnical/Structural/Nonstructural Performance* – A fundamental understanding of the performance of components serves as a basis for performance simulation. Performance includes conventional representations such as strength and deformation capacity, but also includes damage parameters such as concrete spalling and its relation to required repair.
- *Geotechnical/Structural/Nonstructural Models* – Fundamental knowledge on performance is incorporated into analytical models (including randomness and uncertainty) that are defined for the facility and serve as a basis for performance simulations.
- *Performance Simulation* – A computer simulation of performance is conducted using the *Geotechnical/Structural/Nonstructural Models* and the *Ground Motion Representation*. The simulation produces detailed information on response parameters, such as interstory drift and nominal strain, which are then related to component damage measures.
- *Impact Assessment* – Ideally the impact is in terms of the three performance measures adopted in this program, namely, direct dollar loss, functional loss, and casualty loss.

- *Decision-Making* – Outcomes from the Impact Assessment lead to decision-making by engineers, owners, lenders/insurers, and government policy-makers and emergency planners.
- *Performance Objectives* – In an assessment or design of an individual facility, the *Impact Assessment* and *Decision-Making* process may be made in the context of established *Performance Objectives* that define what impacts are acceptable. When impacts are not acceptable, performance objectives may change, or the system may require redesign to match the objectives.
- *Methodology Application* – The methodology being developed by PEER involves the application of all the steps of the process identified in Figure 2.3. As a convenience for the graphic only, the term *Methodology Application* is shown within an inner loop that corresponds to assessment of a facility, as opposed to design. Assessment is a primary focus of PEER research up to Year 6. As PEER moves forward in Years 7 through 10, plans are in place to expand this focus to include design. As that occurs, the *Methodology Application* will move to the outer loop to encompass the entire process.

2.1.2.2 Formalization of the Methodology.

Two unifying features of the PEER program are integration of the simulation/information technology tools and the formalization of a common methodology for performance assessment. Given the inherent uncertainty and variability in seismic response, it follows that the assessment methodology should be formalized with a probabilistic basis. Referring to Figure 2.4, PEER's probabilistic assessment framework is described in terms of four main analysis steps (hazard, structural, damage and loss), the outcome of which is described in terms of a specific variable. Moving from left to right in Figure 2.4, the four steps directly follow from the methodology introduced in Figure 2.3. The outcome of each step is mathematically characterized by the four generalize variables: *Intensity Measure (IM), Engineering Demand Parameter (EDP), Damage Measure (DM)*, and *Decision Variable (DV).* Recognizing the inherent uncertainties involved, these variables are expressed in a probabilistic sense as conditional probabilities of exceedance, i.e., $p[A \mid B]$. Underlying the approach in Figure 2.4 is that the performance assessment components can be treated as a discrete Markov process, where the conditional probabilities between parameters are independent.

The first assessment step entails a hazard analysis, through which one evaluates one or more ground motion *Intensity Measures (IM)*. For standard earthquake intensity measures (such as peak ground acceleration or spectral acceleration) the *IM* is obtained through conventional probabilistic seismic hazard analyses. Typically, the *IM* is described as a mean annual probability of exceedance, $p[IM]$, which is specific to the location (O) and design characteristics (D) of the facility. The design characteristics might be described by the fundamental period of vibration, foundation type, simulation models, etc. In addition to determining the *IM*, the hazard analysis involves characterization of appropriate ground motion input records for time history analyses. PEER's research on hazard analysis involves close coordination with the earth science and engineering seismology communities both to improve the accuracy of determining conventional scalar *IM*s and to investigate alternative seismic intensity measures that best correlate with earthquake-induced damage. These alternative measures may include vector representations of multiple intensity measures, such as multiple representations of spectral acceleration, spectral shape, and duration.

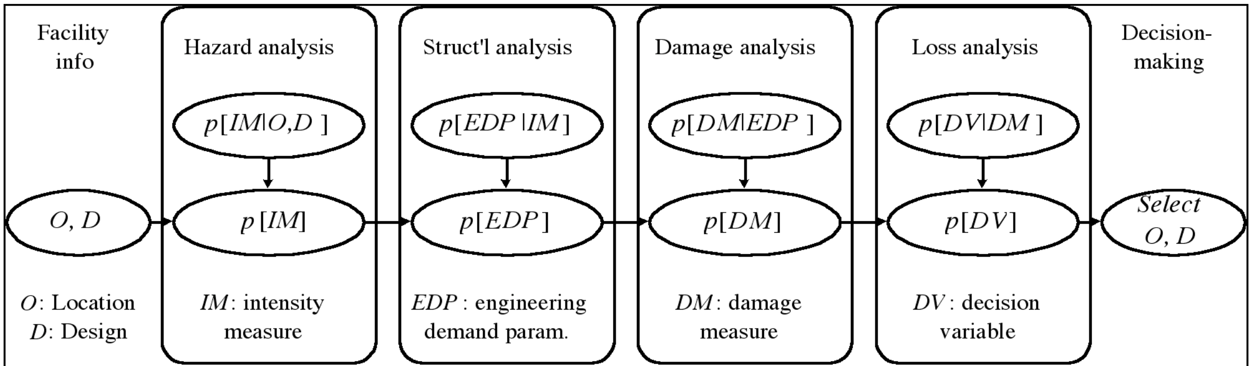


Figure 2.4 – Underlying probabilistic framework of PEER's performance-based earthquake engineering framework

Given the *IM* and input ground motions, the next step is to perform structural simulations to calculate *Engineering Demand Parameters (EDP*), which characterize the response in terms of deformations, accelerations, induced forces, or other appropriate quantities. For buildings, the most common *EDP*s are interstory drift ratios, inelastic component deformations and strains, and floor acceleration spectra. Relationships between *EDP* and *IM* are typically obtained through inelastic simulations, which go to the essence of PEER's research on developing and implementing structural, geotechnical, SSFI (soil-structure-foundation-interaction), and non-structural damage simulation models. PEER has developed various approaches, such as the incremented dynamic analysis technique, to systematize procedures for characterizing the conditional probability, $p(EDP|IM)$, which can then be integrated with the $p[IM]$, to calculate mean annual probabilities of exceeding the *EDP*s.

The next step in the process is to perform a damage analysis, which relates the *EDP*s to *Damage Measures, DM*, which describe the physical damage and resulting consequences to a facility that can then be related to the *Decision Variables, DV*. The *DM*s include descriptions of damage to structural elements, non-structural elements, and contents, in order to quantify the necessary repairs along with functional or life safety implications of the damage (e.g., falling hazards, release of hazardous substances, etc.). PEER is developing conditional damage probability relationships, $p(DM|EDP)$, for a number of common and representative components, based on published test data, post earthquake reconnaissance reports, and tests of a few select components. These conditional probability relationships, $p(DM|EDP)$, can then be integrated with the *EDP* probability, $p(EDP)$, to give the mean annual probability of exceedance for the *DM*, i.e., $p(DM)$.

The final step in the assessment is to calculate *Decision Variables*, *DV*, in terms of mean annual probabilities of exceedance, $p[DV]$. Generally speaking, the *DV*s relate to one of the three decision metrics discussed above with regard to Figure 2.2, i.e., direct dollar losses, downtime (or restoration time), and casualties. In a similar manner as done for the other variables, the *DV*s are determined by integrating the conditional probabilities of *DV* given *DM*, $p(DV|DM)$, with the mean annual *DM* probability of exceedance, $p(DM)$. PEER's previous research has served to, first, establish the choice of appropriate *DV*s and ways of presenting these performance metrics to stakeholders and, second, develop loss functions describing $p(DV|DM)$ relationships.

The methodology just described and shown in Figure 2.4 is an effective integrating construct for both the PBEE methodology itself and the PEER research program. The methodology equation provides researchers with a clear illustration of where their discipline-specific contribution fits into the broader scheme of PBEE. Moreover, the equation emphasizes the inherent uncertainties in all phases of the problem and provides a consistent format for sharing and integrating data and models developed by researchers in the various disciplines.

2.1.1.3 Proof-of-Concept Testbeds.

Beginning in Year 5 (October 2001), PEER established a series of proof-of-concept testbeds as identified within ovals in the *Technology Integration Plane* of Figure 2.1. These testbeds had the multiple objectives to: focus and integrate the multidisciplinary research; test research products and identify needed research; and provide a mechanism for PEER researchers and Business and Industry Partners to work jointly on research.

Figure 2.5 – Van Nuys building

The testbeds are real facilities or inventories of facilities containing seismic environments, geologic conditions, and construction types representative of those of interest in the PEER program. The following paragraphs describe the testbeds:

Figure 2.6 – Examples of equipment in UC Science Building

Van Nuys Building – This older concrete building (Figure 2.5) has deficiencies typical of many buildings in the western U.S. Past earthquake performance records make it suitable for verifying analytical approaches. Testbed studies include: performance assessment; retrofit solutions and ensuing challenges of SSFI analysis; and new design options for buildings of similar configuration. Aspects of life safety, cost, and downtime are being considered in each case.

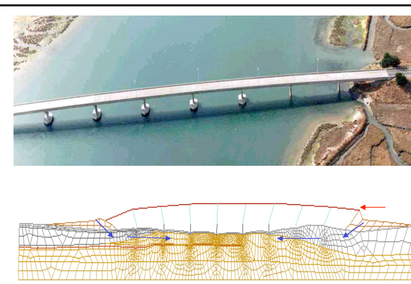


Figure 2.7 – Humboldt Bay Bridge

UC Science Building – This relatively new building has nonstructural systems and valuable lab equipment and experiments (Figure 2.6) that dominate performance decisions. It is a critical research facility on the UC Berkeley Campus, with research involving hazardous and irreplaceable samples. Testbed studies include: performance of nonstructural systems; performance of research equipment including issues related to life-safety, egress, and replacement; and cost and benefits of nonstructural mitigation.

Humboldt Bay Bridge – Caltrans has found this older bridge to be vulnerable and to require retrofit (Figure 2.7). The site is susceptible to strong ground shaking with potential soil liquefaction, approach fill settlement, and lateral spreading. Thus, it is an excellent example where comprehensive simulations of the super- and sub-structure responses are necessary to accurately evaluate performance. Testbed studies include: impacts of permanent ground deformation and seismic retrofit options and impacts.

I-880 Interchange Bridge – A modern reinforced concrete bridge viaduct (Figure 2.8) this testbed is part of the I-880 highway constructed in the mid-1990s as part of the Caltrans Cypress Replacement Project in Oakland, California. It provides a linkage between a bridge-specific study of performance and the highway network study. The viaduct consists of a box girder, supported on multi-column bents of modern ductile design, with cast-in-steel shell concrete pile foundations. Testbed studies include: soil-pile-structure interaction, performance of conforming concrete details, P-delta effects, the response of multiple frames on different types of soils, and evaluation of bridge functionality and repair costs.

Figure 2.8 – I-880 Bridge

Disaster-Resistant Campus – The UC Berkeley campus is located directly adjacent to the Hayward fault (Figure 2.9), has been a FEMA Disaster-Resistant Campus, and has an extensive seismic retrofit program under way. Testbed studies include: documentation of the potential losses; design criteria; quantifying the change in potential losses based on enumerated performance standards; and study of decision-making processes associated with setting a priority system for seismic upgrades. Moreover, it provides a vehicle for assessing the interdependence of the performance of the Life Sciences Addition Building to the campus network of which it is a part.

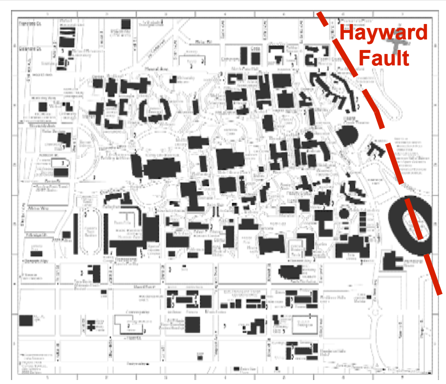


Figure 2.9 – UC Berkeley Campus

San Francisco Bay Area Network – The Bay Area highway system plays an important role in the regional economy, is highly complex with limited redundancy, and is exposed to high and near-fault seismicity. The system includes over 2600 bridges, among which are several major bay crossings, and has been subject to extensive assessment and retrofit by Caltrans. Testbed studies include: potential direct and indirect economic losses following a major earthquake; interdependence of bridge performance on the network performance; and effect on system performance of various design objectives, including retrofitting objectives.

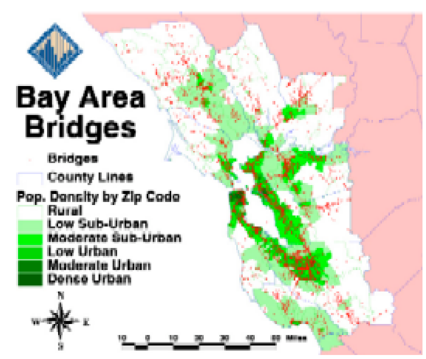


Figure 2.10 – Highway Network

Specific efforts on each of these testbeds as just described have served an important role to help integrate the PEER research in Years 5 and 7. Details on the coordination and progress are available on-line at *http://www.peertestbeds.net*. Specific focus on these testbeds will wind down at the end of Year 6 and, outcomes from the testbeds will be the focus for PEER's Annual Meeting in Year 7. As described later, the current testbed effort will lead into new integrating projects focusing on building performance, bridge performance, and a new tri-center initiative on the performance of geographically distributed systems.

2.1.3 Enabling Technologies Plane

The systems studies of the *Technology Integration* (upper) plane of Figure 2.1 require *Enabling Technologies,* organized within the middle plane of Figure 2.1. Central to the enabling technologies are two software platforms currently under development – *OpenSees* and the *Network Platform*. These software platforms integrate other enabling technologies including ground motion libraries and various analytical models; they are to be supported by various visualization and information technologies. The two computational platforms are tested using data from various laboratory tests as well as data recorded during past earthquakes. Detailed descriptions of these platforms follow:

- *OpenSees* – The *Open System for Earthquake Engineering Simulation* is an advanced performance simulation software framework for structural and geotechnical systems. The software is designed facilitate development and implementations of models for structural behavior, soil and foundation behavior, and damage measures. Unlike traditional "codes," *OpenSees* is designed and implemented in a modular, object-oriented manner with a clearly defined application program interface (API). The modules for modeling, solution, equation solving, databases, and visualization are independent, which allows great flexibility in combining modules to solve classes of simulation problems. The modular design allows researchers from different disciplines, such as geotechnical and structural engineering, to combine their software implementations. In addition, parallel and distributed equation solvers developed by computer scientists and mathematicians are integrated into the framework for simulation of very large models.

  Beginning in Year 6, PEER researchers have begun to develop simulation methods for use in NSF's George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program. The open architecture of *OpenSees* from the beginning was designed to provide support for combining computational simulation with advanced experimental methods, such as the pseudo-dynamic test method. In effect, the *OpenSees* interface can treat a physical component test as an element or subassembly, thereby serving as a platform for hybrid control of physical experiments. In addition, *OpenSees* supports parallel processing, which will become increasingly important for solving large problems on the NEES grid.

  OpenSees plays an important role in education because students are more motivated to learn about computer science and advanced applications once exposed to the modern computing and software approaches incorporated in *OpenSees*. The software is "open source," meaning that all parts of the code are available for users to see, check, track changes, and contribute to. The *OpenSees* website (*opensees.berkeley.edu)* is being continually maintained and enhanced to provide up-to-date downloads, source-code tracking, and communication. This is the first instance of an open-source, community software in earthquake engineering. Currently, more than 300 users are automatically notified of updates in the *OpenSees* software repository, an indicator that the earthquake engineering community that follows *OpenSees* developments is growing.

  Validation of models incorporated into *OpenSees* is necessary to document their capabilities (and limitations). In addition to validation of material and component models, *OpenSees* is being used in comprehensive validation of the system behavior of buildings and bridges. In Year 6, the testbed projects have been validating the models used in the structural and geotechnical simulations. The simulation and validation activities for the testbed projects include:

- *Component Simulations* – The analytical models developed within the *Enabling Technologies Plane* (Figure 2.1) were derived mainly from physical experiments on components. These individual physical tests serve as one form of testbed for *OpenSees*.
- *System Simulations* – Recorded earthquake response data for the Van Nuys testbed building and Humboldt Bay Bridge have provided an excellent opportunity to implement and refine *OpenSees*. Additional system simulations will be possible as part of ongoing or planned earthquake simulation tests on building and bridge framing systems.
- *Performance Databases* – System simulations generate a large amount of data, and the data must be statistically processed for determining performance characteristics. The testbeds provide an ideal opportunity to utilize the databases, and the connections between *OpenSees* and the databases, for performance evaluation.

• *Network Platform* – Through PEER's Highway Demonstration Project, a suite of analysis and GIS database software has been assembled for simulating the seismic performance of highway networks. The platform is set up for the San Francisco Bay Area highway network, and incorporates detailed data describing geographically distributed seismic hazards, bridge descriptions, and transportation links. This platform is unique from other geographically distributed loss analysis systems in that it links transportation network analysis software with data on damaged bridges obtained from a comprehensive seismic risk analysis. Other regional loss programs, such as HAZUS, consider the direct loss only to bridges. The Network Platform is based on detailed simulations of scenario earthquakes, resulting in predictions of bridge damage and the resulting disruptions (measured in traffic delay times) to the transportation system. A recent focus has been to extend the simulation to evaluate how the transportation disruption impacts economic activity sectors, which in turn affects origin-destination traffic demands on the network. The outcomes are an understanding of the highway system performance (important for post-earthquake response and recovery) and an estimate of the expected loss, including both direct and indirect costs.

Beginning in Year 6, development of the Network Platform will be incorporated under a new EERC Tri-Center Initiative on Geographically Distributed Lifeline Systems. As outlined in Volume III of this report, the tri-center initiative will focus primarily on highway and electric utility lifeline systems. In addition to the core programs of the three EERCs (PEER, MAE, and MCEER), the initiative will involve the PEER-Lifelines Program, the MCEER-FHWA program, and externally funded Caltrans research. As part of the tri-center agreement, PEER has agreed to orient its bridge performance and highway risk analysis efforts to be compatible with a seismic risk assessment program, called REDARS, whose core development is supported by MCEER-FHWA. With regard to the Network Platform, PEER envisions that its research focus will be to improved modular components of REDARS and to utilize REDARS in studies of system performance. PEER's specific research contributions will include development of improved models for evaluating bridge performance, hazards due to ground shaking and ground deformation, and characterization and propagation of uncertainties in the risk assessment methodology. A related longer-term goal of both the tri-center initiative and PEER is to explore ways of extending the highway network models to evaluate electric utility systems. Further details on these activities are summarized in the Volume III report.

- *Other Enabling Technologies* – Other enabling technologies, which appear in Figure 2.1 include:
  - *Hazard Models* – the hazard models represent the seismic hazard in terms of magnitude, mechanism, recurrence; define attenuation of ground motion parameters to the site; and facilitate selection of representative ground motions, including an online ground-motion database.
  - *Geotechnical Simulation and Performance Models* –the simulation models model the mechanical behavior (e.g., load-deformation response) of various components/media, while the performance models relate performance to the various stages of mechanical behavior.
  - *Structural Simulation and Performance Models* – these are the structural parallels to the *Geotechnical Simulation and Performance Models.*
  - *Nonstructural Simulation and Performance Models* – these are the nonstructural parallels to the *Geotechnical Simulation and Performance Models.*
  - *SSFI Models* – soil-structure-foundation interaction models are needed to supplement geotechnical and structural models.
  - *Reliability Framework and Tools* – these include procedures for selecting modeling parameters, frameworks for assessment methodologies (e.g., Equation 1), and implicit and explicit analytical procedures embedded within OpenSees and the Network Platform.
  - *Loss Assessment Techniques and Tools* – these provide linkages between physical performance measures such as damage and the economic or other social impacts, for use in both OpenSees and the Network Platform.
  - *IT Tools* – these include (a) the development and use of visualization tools to improve ways of expressing performance, and (b) networks and databases to facilitate computation and sharing of information.

2.1.4 Knowledge Base Plane

The enabling technologies of the middle plane of Figure 2.1 are built upon fundamental studies in the lower *Knowledge Base* plane. Studies on this plane include seismic hazard characterization studies; geotechnical, structural, and nonstructural performance studies to define behavior models and performance parameters; and studies of risk analysis and decision-making. The studies within this plane are aimed primarily at supporting model development or computer platform validation, and therefore are defined largely by the research needs of the middle and upper planes of Figure 2.1.

2.2 Overview of Thrust Area Research Organization, Outcomes, Milestones, and Projects

The Needs and Requirements described in Section 2.1.1 define in a broad sense the ultimate goals of the PEER research program; and descriptions of the Integration, Enabling Technologies, and Knowledge Base Planes in Sections 2.1.2 through 2.1.4 highlight significant research focus areas and products. This section, together with subsequent sections of this chapter, provides further details of the research program organization and specific milestones as related to the needs for implementing PBEE. Section 2.2.1 begins with a brief overview the research organization, followed with a description of thrust area research coordination and milestones (Section 2.2.2) and a list of Year 6 and 7 research projects (Section 2.2.3 and Table 2).

2.2.1 Research Organization

PEER carries out research within two administratively distinct but coordinated programs. The *Core Research Program* is that portion of the program supported by the core NSF funds and matching funds. That program has the objective of developing the overall methodology for PBEE. The Core Research Program is complemented by the *Program of Applied Earthquake Engineering Research for Lifeline Systems*, commonly referred to as the Lifelines Program. The Lifelines Program is designed to satisfy the unique needs of the industry and government sectors providing the funds for the program. The Lifelines Program was established early in the life of PEER under a contract with specific administrative requirements. In the first two years of PEER, the two programs operated almost entirely separately. Starting in Year 3, PEER began to implement coordination mechanisms, and in subsequent years, PEER developed a center-wide strategic planning mechanism to encompass the two programs.

The research program is organized into five thrust areas. The thrust areas are defined to fit our vision for PBEE, as illustrated by the flowchart of Figure 2.3. The different thrust area topics that overlap are shown in the flowchart – the overlap reflects and contributes to the integration of research. The five thrust areas and their primary focus areas are described below:

- *Loss Modeling and Decision-making* – The goals of the thrust area are to provide the necessary fundamental knowledge concerning decision-making and costs associated with earthquakes, to develop tools for economic evaluation of PBEE, and to contribute to the systems integration of PBEE through integration of decision and economic components of testbeds and other PEER outcomes.
- *Hazard Assessment and Geo-Performance* – This thrust area is directed toward definition of the seismic hazard, toward simulation of site response, and soil-foundation-structure-interaction (SSFI), and toward evaluation of the relationship between ground response/failure and performance.
- *Assessment and Design Methodologies* – The objective of this thrust area is to develop a comprehensive reliability-based methodology for socio-economic and engineering performance assessment and design. Projects concerned specifically with testbed activities and coordination are incorporated in this thrust area.
- *Simulation and Information Technologies* – The goal of this thrust area is to improve the capability for evaluating seismic demands on geotechnical, structural, and non-structural systems with the ultimate objective of developing realistic system simulations.
- *Structural and Non-Structural Performance* – The objective of this thrust area is the development of robust mathematical models (for mechanical modeling and performance assessment) of structural and nonstructural components, sub-assemblages and systems through experimentation and analysis.

2.2.2 Research Needs, Outcomes, and Integrative Milestones

The graphic in Figure 2.11 shows an overview of how various components of the research program are coordinated to respond to the needs for PBEE, which represent the desired outcome

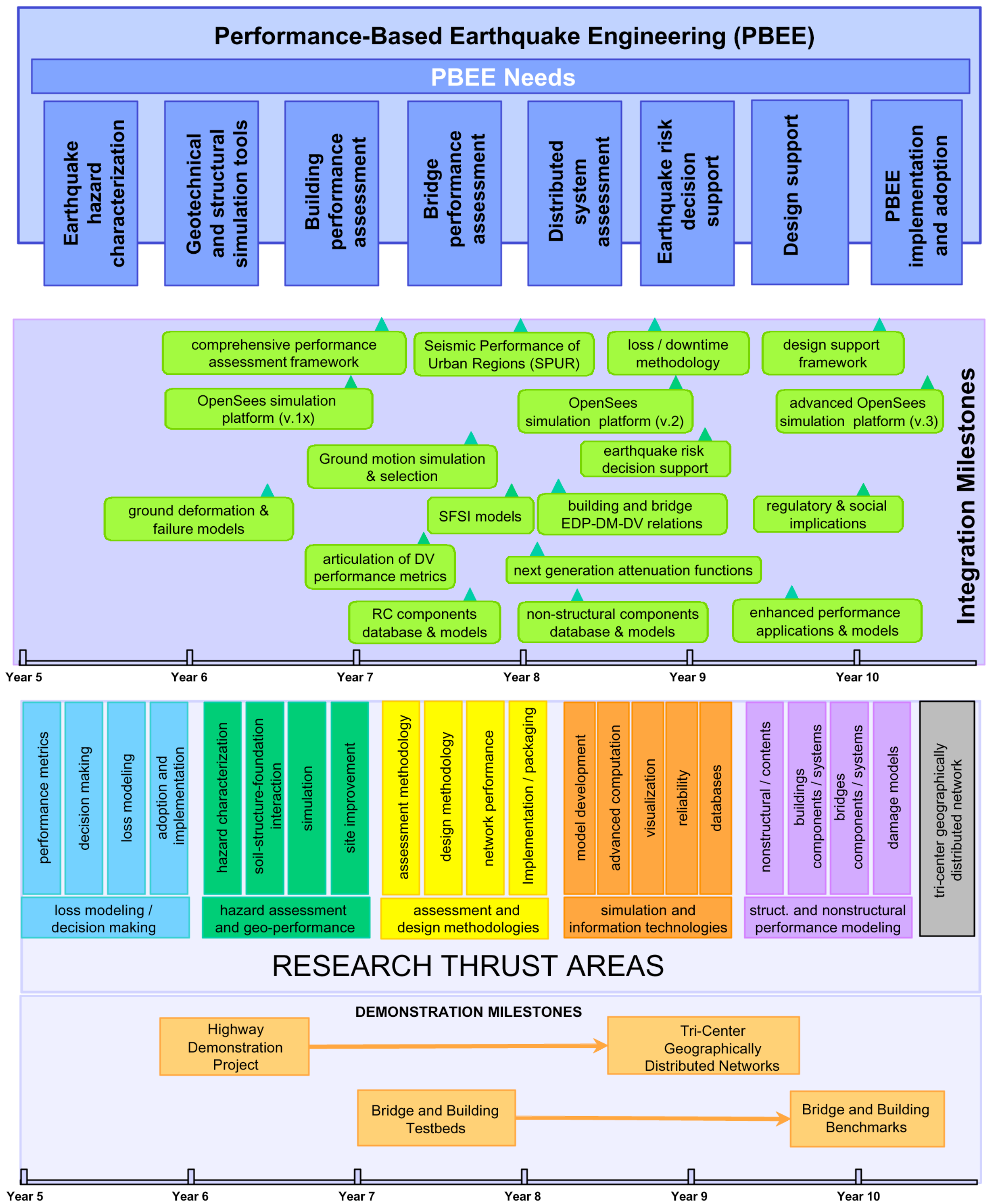


Figure 2.11 – Outcomes, Integrative Milestones, and Thrust Areas

of PEER's research. At the top of this figure are eight specific topics, which articulate the specific PBEE Needs. Immediately below these PBEE Needs are a series of Integration Milestones, which are the culmination of specific research achievements by one or more thrust areas. The Integration Milestones are organized left to right in time, and the vertical arrangement represents in some sense a hierarchy among the milestones (i.e., with ones on the bottom tending to feed into those above). Below the Integration Milestones are the five research thrust areas and the topical areas within each thrust. Finally, at the bottom of the figure are demonstration milestones.

To maintain readability of Figure 2.11, graphical links connecting the topical research areas to integrative milestones to the PBEE Needs are not shown. However, linkages are considered in PEER's strategic planning and are evident in the detailed thrust area strategic plans discussed later in this chapter. Further details on the PBEE Needs, Integration Milestones, and Demonstration Milestones are given in the following subsections.

2.2.2.1 Research Needs and Outcomes

As described earlier, the overall needs for PBEE are to address three levels of earthquake risk decision-making. To meet these global needs, the following specific needs and desired outcomes of the PEER research program have been defined:

- *Earthquake Hazard Characterization:* Data, improved models, and guidelines to more accurately describe earthquake hazards due to ground shaking and ground deformation (including liquefaction and fault rupture). Included is the definition of appropriate seismic hazard Intensity Measures (IM) and input ground motions.
- *Geotechnical and Structural Simulation Tools:* Computational models, data, and criteria for accurate simulation of building and bridge facilities, including (where necessary) the foundations and surrounding site.
- *Building Performance Assessment:* Comprehensive methodology with supporting data, models, and computational tools to conduct detailed probabilistic assessment of earthquake losses to buildings. Losses are characterized in terms of direct financial losses, downtime (loss of functionality), and casualty predictions. Primary emphasis is on buildings with either ductile or non-ductile (conforming or non-conforming) reinforced concrete frame systems.
- *Bridge Performance Assessment:* Comprehensive methodology with supporting data, models, and computational tools to conduct detailed probabilistic assessment of earthquake losses to reinforced concrete bridges. Loss emphasis is on bridge damage leading to bridge closure or reduced functionality and estimates of restoration time and costs.
- *Distributed System Assessment:* Methodology with supporting data, models and computational tools to conduct probabilistic assessment of earthquake losses to geographically distributed lifeline systems. Emphasis is on reduced traffic capacity (leading to delays and other disruption) to highway and major arterial transportation networks in California due to bridge damage; and disruption of electric utility networks, due to earthquake damage to substation equipment and buildings.

- *Earthquake Risk Decision Support:* Collection of methodologies, case studies, and financial models to assist stakeholders in utilizing PBEE to make more informed decisions concerning earthquake risk management.
- *Design Support:* Methodologies and modeling simplifications to apply PBEE assessment techniques to make design decisions for new buildings and bridges. Emphasis is on guidelines for modifying performance objectives through altering of engineering demand parameters, which correlate most closely with decision variables.
- *PBEE Implementation and Adoption:* Background information, guidelines, and strategies to facilitate implementation of PBEE techniques in practice and building codes and standards.

2.2.2.2 Integrative Milestones

The Integrative Milestones shown in Fig. 2.11 are ones resulting from contributions of two or more thrust areas, either directly from the thrust areas or indirectly by linkages with other integrative milestones. Highlights of each milestone are as follows:

- *Comprehensive performance assessment framework* – detailed specification of all major steps in determining input data, conducting simulations, and processing uncertainties for comprehensive performance assessment of individual facilities, employing the IM-EDP-DM-DV path.
- *Loss/downtime methodology* – methodology for probabilistic assessment of direct dollar losses and facility downtime, intended to improve upon due-diligence evaluations (e.g., Probable Maximum Loss, PML) of facilities for better informed risk management decisions by owners and financial/insurance institutions.
- *Design support framework* – methodology, criteria and guidelines for performance based design of new and existing structures. Emphasis will be on ways to alter and target desired performance objectives by design parameters for the foundation, structural and nonstructural components, and contents.
- *OpenSees simulation platform (v1, v2, v3)* – version updates of OpenSees with new modeling and computational capabilities. The final version 3 will have advanced network-enabled computational, database, and visualization features.
- *Seismic Performance of Urban Regions (SPUR)* - demonstration of integrated simulation and visualization platform for earthquake ground motions and their effects on urban infrastructure facilities. Refer to Section 2.6 for further details of this collaborative project, which makes use of earthquake hazard and simulation research from Thrust Areas 2 and 4.
- *Earthquake risk decision support* – guidelines and examples for utilizing seismic performance metrics to make risk management decisions, based on multiple considerations including benefit-cost, investment trade-offs, business interruption planning, etc.
- *Regulatory and societal implications* – evaluation and benchmarking of present building code regulations and other societal factors related to the adoption and acceptance of performance-based building codes. Included will be critiques of PBEE relative to current design practice, considering observations from testbed and benchmark studies.

- *Ground motion simulation and selection* – data, models, and procedures for defining seismic hazard and input ground motions for simulation and performance assessment of buildings, bridges, and other facilities.
- *Building and bridge EDP-DM-DV relations* – data and models to relate engineering parameters to damage and quantifiable decision variables for buildings and bridges. For buildings, emphasis will be on collapse and losses associated with damage to structural and nonstructural components, repair costs, and occupancy interruption. For bridges, the major decision variables relate to traffic closure and restoration times.
- *Next generation attenuation functions* – culmination of work to incorporate expanded and improved ground motion data into improved attenuation functions for spectral acceleration and other IMs as a function of earthquake magnitude and distance from site.
- *Soil Foundation Structure Interaction (SFSI) models* – implementation, validation, and documentation of OpenSees simulation models for shallow and deep foundations, with applications to bridges and buildings.
- *Articulation of DV performance metrics* – consensus on key decision variables and preferred ways of articulating these decision variables for different stakeholders.
- *RC component database and models* – data and models for simulation of structural response and damage to reinforced concrete components, including beams, columns, joints (column splices, beam-column, slab-column), and walls.
- *Nonstructural component database and models* – data and models to evaluate seismic damage and consequences to nonstructural building components and contents. Organized around a comprehensive taxonomy, data and models will be developed based on published literature and selected tests conducted by PEER.
- *Enhanced performance applications and models* –component models, simulation tools, and benchmark studies to evaluate performance of enhanced reinforced-concrete systems, which through use of new concepts or materials provide cost-effective alternatives to conventional systems.

2.2.2.3 Demonstration Milestones

Referring to the demonstration milestones at the bottom of Figure 2.11, PEER has emphasized demonstrating the application of PBEE in two major areas – (1) individual bridge and building facilities, and (2) transportation networks and other distributed systems.

Beginning in Year 5 and scheduled to conclude early in Year 7, applications to buildings and bridges have been through the four proof-of-concept testbeds, which were described in Section 2.1.2.3. Beginning Year 7, emphasis will shift to generalized studies on performance assessment and benchmarking of modern reinforced concrete buildings and bridges. Like the proof-of-concept testbeds, the benchmarking exercises will serve to integrate and focus the interdisciplinary research and provide a mechanism for packaging consistent assessment methodologies. Additionally, the change in emphasis from studies of specific testbed facilities to generalized classes of facilities will serve the emerging needs for design and system considerations. For both buildings and bridges, the benchmark studies will provide data on the reliability and implicit target performance of current codes, which was a high priority research need identified in discussions with researchers and industry partners at the 2003 PEER Annual

Meeting. In addition to providing a benchmark against which to gage socially acceptable performance targets, these studies will highlight opportunities for improving design procedures, with emphasis on understanding how changes in key design parameters (strength, stiffness and ductility) affect the seismic performance. For bridges, the benchmark studies will lead to improved fragility models, which will be used in highway network studies to help establish appropriate performance targets for bridges.

The second major demonstration area concerns the inter-relationship between the performance of individual facilities and the networks of which they are a part. Year 5 marked a major milestone for the Highway Demonstration Project, which involved a seismic risk analysis of the San Francisco Bay Area highway network. This effort involved developing and applying computational tools to assess bridge damage and the resulting transportation delays (travel times) under likely earthquake scenarios. Beginning in Year 6, research on the highway network performance will be coordinated under the tri-center initiative on geographically distributed networks. Evaluation of the road networks will continue as a major effort under this initiative, but with an expanded focus to adapt and combine aspects of risk analysis for other lifeline networks. Specific details on the scope of the demonstration exercise are still being developed by the tri-center coordinating committee, with the expectation that the tri-center demonstration studies will leverage PEER's previous work on the Bay Area Highway Demonstration Project.

2.2.3 Year 6 and 7 Research Project Summary

Research projects for the current Year 6 and those proposed for Year 7 are summarized according to thrust areas in Table 2 (located at the end of this chapter). Detailed summaries of all current (Year 6) projects are included in Volume II of this report. Each project is identified with a project number, principal investigator (PI), and title. These project identifiers are referenced in the thrust area research summaries in Sections 2.3 through 2.7. Project numbers of the form xyz2002 (or xyz2003) refer projects that are administered through the Core research program. Projects with other three digit numbers (e.g., 701), or three digits plus one letter (3G02) are those administered through the Lifelines Program. Details of the administrative management structure for the Core and Lifelines projects are summarized later in Section 2.8.

Funding amounts specified in Table 2 for Year 6 are the direct research expenses, i.e., neglecting administrative and other indirect costs applied to projects. Funding amounts for proposed Year 7 projects are for the total budgeted amount (direct plus indirect costs), since the detailed project budget breakdowns for Year 7 projects are not yet available. There are a couple new Year 7 projects, where the project PI and funding allocation are undetermined at this time, pending final accounting of residual funds from Years 5 and 6 that are available for Year 7.

2.3 Thrust Area 1 - Loss Modeling and Decision-Making

2.3.1 TA 1 Goals

The goals of the thrust area are to provide the necessary fundamental knowledge concerning decision-making about seismic improvements, to develop necessary data and tools for assessing losses and costs associated with different predicted damage states, and to contribute to the systems integration as it relates to the adoption and societal implications of PBEE. This area contributes to the definition of performance goals and measures, to evaluation of the impacts of performance-based improvements, to strategies for disseminating PBEE tools and frameworks, and consideration of the societal implications of PBEE. These topics address the "front end" (design) and "back end" (implementation and evaluation) of PEER's development of PBEE. While a variety of studies have been undertaken by social scientists that address various aspects of estimation and mitigation of earthquake losses, the PEER component is distinguished by the focus on performance-based approach and by integration of the socio-economic component with engineering considerations.

2.3.2 TA 1 Strategic Plan

The strategic plan for this thrust area (see Figure 2.12) calls for continuing research concerning three components: (1) decision considerations – contribution to fundamental knowledge on the basis for PBEE decisions, the framing of decisions, financial and other tools for evaluating PBEE choices, and the presentation of PBEE analytic findings and their tradeoffs; (2) modeling of losses and costs – understanding as fundamental knowledge of the losses and costs associated with structural and nonstructural damage to facilities as critical for understanding the consequences of different levels of damage; and (3) implementation of PBEE tools and frameworks — consideration of the barriers to and implications of performance-based regulation. Beginning with Year 6, the PEER efforts in this area placed stronger emphasis on practical lessons from the testbeds for decision-making and economic analysis. The Year 7 research capitalizes on these lessons by addressing key research gaps with attention to broader contributions to the PEER assessment methodology.

2.3.3 TA 1 Critical Mass and Level of Effort

The researchers contributing to this thrust area represent a broad cross section of social science and engineering disciplines: architecture, decision-making, finance, planning, public policy, regional system sciences, and construction cost-estimating. The fact that this area comprises about one-sixth of the PEER core program budget shows that there is substantial commitment and effort to this area. PEER has been successful in recruiting a number of highly talented investigators who had not previously studied earthquake risks.

2.3.4 TA 1 Research Advances and Deliverables

The typical outcome and contribution of social science research is new understanding that influences the design of tools or products produced under other aspects of PEER's research. As such, the impact of this research should be measured in terms of its relevance and contributions to design, implementation, and evaluation of PBEE tools and frameworks, rather than specific outputs.

Researchers within this thrust area have been collaborating with other PEER researchers in a number of areas. In addition to the integrative activities of the testbeds, joint research activities have included studies of decision-making by firms about seismic choices (Meszaros TA1 with Lehman TA 5), financial modeling of losses (Ince with Miranda TA 1), studies of life-safety considerations as part of loss modeling (Shoaf TA1 with Miranda TA 1 and Cornell TA 3), and a study of barriers to adoption of PBEE innovations (May TA1 with Stanton TA5). In addition, PEER social science researchers have been collaborating on a number of activities with social scientists at the other engineering earthquake research centers. As discussed in Volume III of this report, this collaboration includes a FEMA-funded project on “guidelines for seismic safety advocates,” involvement of multiple investigators from the centers in the ATC 58 project, and regular meetings of social scientists to discuss research projects.

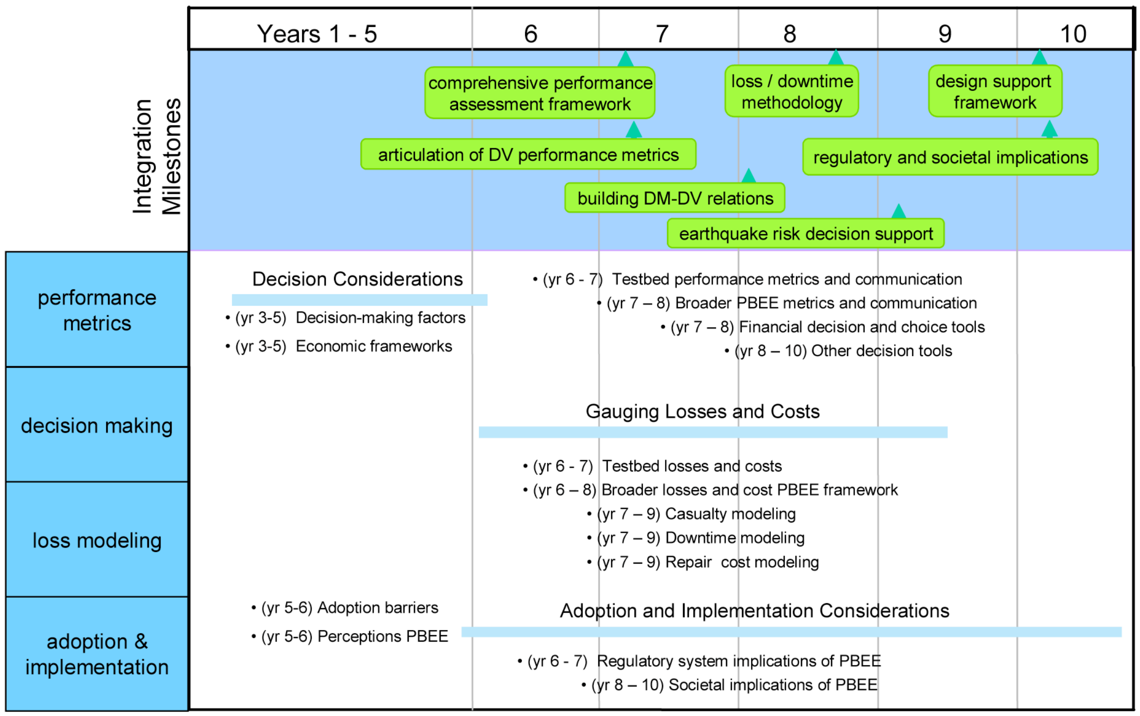


Fig. 2.12 Strategic Plan – TA 1 Loss Modeling and Decision Making

The research from the TA1 thrust area has been presented at a number of conferences (EERI annual meeting, International Sociological Association, US-Japan Joint Workshop, Law and Society Association annual meeting, Pacific Conference on Earthquake Engineering) and is or will be appearing in a number of social science and engineering related journals (*Earthquake Spectra*, *Environmental Hazards*, *Natural Hazards Review*, *State and Local Government Review*).

Significant research contributions of the decision-making and loss modeling components of PEER research include the following:

- *Decision Considerations:* Research in years 2 to 5 on decision-making about seismic safety in a variety of settings has led to identification of key decision considerations for evaluating performance: life-safety, repair costs, and downtime. Overarching these is a broader concern with "the risk of ruin." The testbed research (Year's 6-7) serves as a laboratory for characterizing these outcomes. One component of this research is probabilistic characterization of the financial tradeoffs involved in choosing alternative approaches to enhancing seismic integrity of a structure. This research is directly relevant to the FEMA funded ATC 58 project for which the PEER findings served as the foundation for an ATC 58 workshop on the characterization of performance considerations.
- *Loss Modeling:* The focus of loss modeling, which began in Year 5, has been characterizing losses for the building testbeds (Van Nuys and UC Science buildings). A detailed probabilistic framework for loss modeling involving structural and nonstructural damage has been developed in the context of the Van Nuys testbed, and work is ongoing to

develop detailed damage-repair cost data for this structure. A detailed inventory of nonstructural laboratory components, shake table testing of the fragility of these components, and identification of potential losses associated with these have been undertaken for the UC Science testbed. Beginning in Year 6, research has been initiated to gain a better understanding of the factors that affect life-safety.

- *Policy, Regulation, and Impediments:* Research in this area has contributed to the broader understanding of issues involved in characterizing earthquake performance – the “fallacy of acceptable risk” – and identification of barriers to adoption and implementation of PBEE innovations. This identification provides an understanding of steps that PEER, and the broader ATC 58 effort, can take to enhance the prospects for effective use of PBEE assessment methodology.

2.3.5 TA 1 Future Plans

Activities will be undertaken in Year 7 and subsequent years with respect to each of the four topics of research in this thrust area:

- *Decision considerations* – Beginning in Year 6 and continuing in Year 7, the emphasis of this component is presentation of PBEE assessments, with attention to ways of communicating tradeoffs and uncertainties in estimates (Meszaros/Ince 125, see Table 2). The goal of this research is to devise effective ways for presenting the results of PBEE analyses and tradeoffs among different choices regarding seismic improvements (e.g., reporting of probabilistic versus deterministic results, gauging and reporting uncertainty in assessments, characterizing financial consequences). An important component of this research is development of financial decision tools for making PBEE choices (Meszaros/Ince 125) and research funding for evaluation of the applicability of existing financial decision tools to PBEE assessments (Reis 128). The testbeds are being used to illustrate different ways of communicating this information and for assessing financial considerations.

- *Modeling of losses and costs* – The Year 6 research has emphasized characterization of losses for the testbeds with initial attention to implications for life safety (Beck/Porter 122, Miranda 118, Shoaf/Seligson 126). The Year 7 research continues these characterizations (Beck/Porter 122, Miranda 118) with additional research that address characterization of the potential for serious injuries (unassigned 127), factors that contribute to downtime, and measurement of repair costs (Comerio 120, Miranda 118). These projects are aimed at filling gaps in understanding of factors that contribute to these components of losses with eventual development of methodologies for assessing each of these potential sets of consequences.

- *Policy and societal considerations* – Beginning in year 6, research in this area has turned attention to the societal implications of the performance-based approach with particular attention to the implications for the regulatory system of shifting from prescriptive to performance-based standards (May 123). This draws attention to the regulatory context for implementing PBEE approaches. Subsequent research will address the broader societal implications of performance-based regulatory approaches.

2.4 TA 2 - Hazard Assessment and Geo-Performance

2.4.1 TA 2 Goals

The hazard assessment and geo-performance research program is directed toward evaluation of the effect of ground motion hazards, prediction and simulation of ground response/deformation, and soil-structure system performance. This thrust area includes elements of ground motion characterization, quantitative assessment of soil-foundation-structure interaction, and ground improvement techniques. The hazard assessment research is considering uncertainties and spatial/temporal variability in ground motion, soil/site conditions, and their influence on performance. The scope is focused on providing direct input towards development of reliability-based global design methodologies, and improved procedures for demand evaluation and loss estimation. Results of the hazard assessment research are being implemented into the OpenSees analytical platform, for evaluation of soil-foundation-structure interaction and ground improvement methodologies.

In general, all efforts include the PEER research theme toward multi-level performance prediction, inclusion of uncertainties, and spatial/temporal variability. The explicit consideration of these factors, and the focus on soil-foundation-structure interaction, are distinguishing features of PEER's research in TA 2. Recent projects entail basic experimental and computational research related to the nonlinear seismic response of shallow foundations, and the important problem of soil-pile interaction under conditions of liquefaction and liquefaction-induced lateral spreading. Collaboration among PEER researchers integrates the experimental, practical, and computational aspects within a unified framework.

Under the PEER Lifelines Program, a number of prominent practice oriented deliverables are now available with continued enhancements and additions (e.g., the PEER Ground Motion Database http://peer.berkeley.edu/smcat/). A new multi-investigator effort has been launched this year to develop next-generation attenuation relationships, which is most timely in view of our increased understanding, and the availability of new more accurate and complete data sets from recent earthquakes.

2.4.2 TA 2 Strategic Plan

Shown in Figure 2.13 is the strategic planning graphic for TA 2, which defines a coordinated sequence of research projects to realistically account for geotechnical and ground motion hazards through improved tools and procedures for PBEE. The PEER Core Program research, which emphasizes simulation model development, is supplemented by significant research on hazards and geotechnical site effects funded by the Lifelines Program. As such, the strategic plan coordinates and optimizes resource utilization in both programs. Referring to the research project summary in Table 2 (end of chapter), there are thirty-seven current research projects, with one or more directed towards (1) definition of seismic ground motions and effect of geotechnical uncertainties on EDPs, (2) refinement of site response and site characterization methodologies, (3) improved tools and procedures for ground response prediction with an emphasis on permanent deformation, (4) validated improved tools and procedures for analysis of shallow and deep soil-foundation-structure systems including permanent ground deformation effects, (5) testing and validation of seismic hazard models and algorithms, (6) development of performance-based computational and design procedures for soil-foundation-structure interaction, soil improvement, and foundation remediation, and (7) three-dimensional (3D)

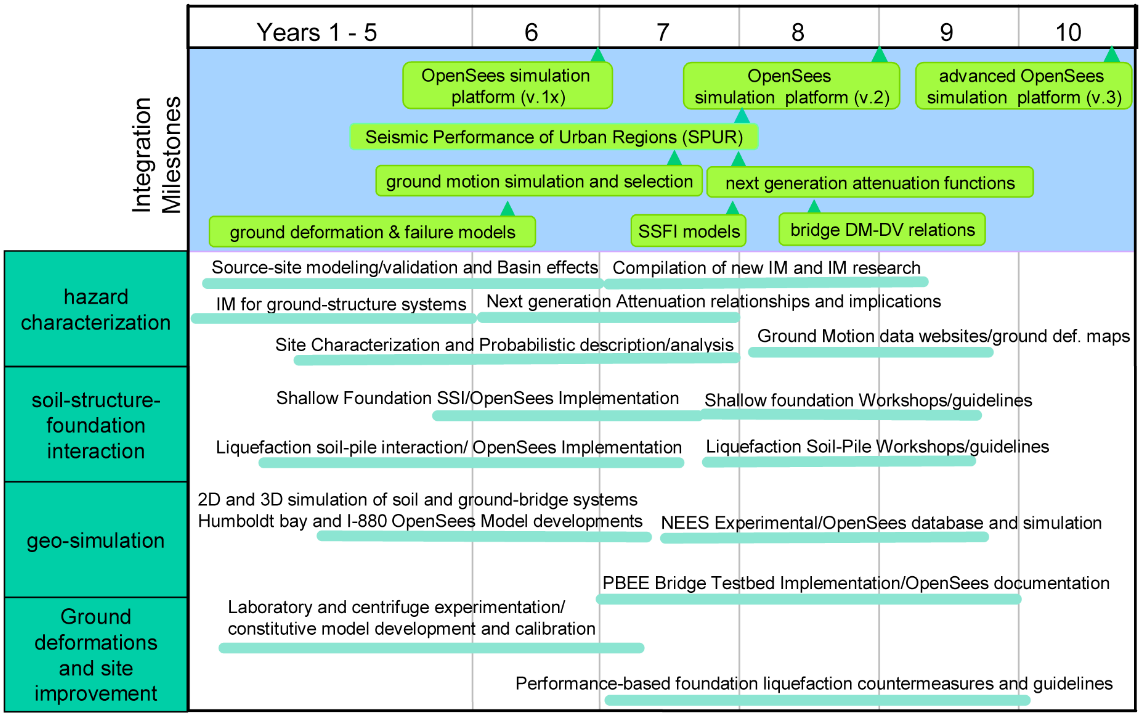


Fig. 2.13 Strategic Plan – TA 2 Hazard Assessment and Geo-Performance

simulation of soil-foundation and soil-structure (bridge) systems. Computational aspects of this research are implemented in the OpenSees platform.

Research on earthquake hazards and ground motions has been ongoing for several years through close cooperation between geotechnical engineers and earth scientists, both within PEER and through collaborations with the Southern California Earthquake Center. Basic research, state-of-the-art numerical simulations, and data from recent earthquakes are employed in the overall framework. d

Building on earlier validated source-to-site 3D numerical simulation validation efforts, a physically based source model is currently being developed (Beroza 1C08). These 3D simulation techniques are now exploring basin effects towards development of simple engineering models (Jordan and Day 1A03). Within the core program, empirical models based on recorded ground motion are complementing this basin effect research (Stewart 225).

Site characterization in southern California continues to progress with SASW and velocity profile testing (Stokoe 2C01, Nigbor 2A02d). This testing contributes significantly to assessments of site condition and the impact thereof on calibration efforts for nonlinear site response analyses (Stewart 2G01).

Ground motion characteristics in California are being addressed by insights from recent recorded data sets in Taiwan (Silva 1E07, Nigbor 2A02d). Simple models for near source fling-type motions are under development (Graves 1L06) for strike-slip and reverse fault scenarios. Use of ground motions within the PEER PBEE framework continues with fundamental studies to identify damaging characteristics and parameters (Bazzurro 1G00). For direct practical applications and seismic studies, a valuable resource is being developed in the form of a Design Ground Motion Library (Power 1F01). This library includes motions categorized by distance and magnitude, through consensus of seismologists, and geotechnical/structural engineers.

In addition to the above, the PEER Lifelines Program has initiated a new topical multi-investigator effort to develop Next Generation Attenuation (NGA) models, based on the latest available information and research insights from recent earthquakes (Power 1L01, and Silva 1L02). Five principal attenuation models are being updated (each by its original developer and co-workers, e.g., Boore et al. 1L03) to include new knowledge related to basin, directivity, and improved site condition effects (Wills 1L05).

Research on soil-foundation-structure interaction SFSI continues this year with shallow (Kutter 226) and deep foundation studies (Boulanger 231). The SFSI shallow foundation research is a coordinated collaborative effort (Kutter 226, Hutchinson 227.2, Martin 227.1) with centrifuge experiments that form a basis for development of calibrated OpenSees models. Relevant data from other experimentation sources worldwide are being incorporated as well. This research is furnishing an important database for cyclic footing-soil interaction, which is generating valuable insights for assessment and design of buildings and bridges. In February 2003, Kutter et al. organized a workshop of geotechnical and structural engineering practitioners and researchers to present the experimental findings and solicit input for future research towards developing calibrated models and criteria for shallow foundation simulation and design.

For deep foundations, liquefaction and lateral spreading effects are currently a main focus. Centrifuge data are being utilized to calibrate OpenSees models (Boulanger 231) for use within the Humboldt Bay Bridge testbed. Full-scale tests funded earlier by the PEER Lifeline program (piles in soil subjected to blast-induced liquefaction and lateral spreading) are being analyzed and used for calibration of OpenSees (Ashford 234), as are data from full-scale axial load tests sponsored by the UC Berkeley Capital Projects Office (Sitar 222).

The above described research efforts are systematically allowing for active development of the OpenSees simulation framework. Significant computational efforts are underway (Elgamal 220, Jeremic 221, Boulanger 231, Hutchinson 227) to incorporate the latest findings for modeling large soil-structure systems, including major efforts on the Humboldt Bay and I-880 Bridge testbeds (Elgamal 220, Conte 413, and Kunnath 325). In conjunction with high fidelity 3D simulations, attention is directed towards spatial definition of input motion, inclusion of radiation boundary conditions, and implementation of the PEER probabilistic analysis framework. A new project by (Kramer and Arduino 235) is specifically dedicated towards assessment of geotechnical uncertainty impacts on EDPs.

2.4.3 TA 2 Critical Mass and Level of Effort

Achieving the objectives for Hazards Assessment and Geo-Performance requires both experimental and analytical contributions, based on insights from observed field response. Researchers with demonstrated experience in high-quality experimental work are conducting these studies, along with investigators that are among the leaders in analytical modeling of soil behavior and seismic response. These researchers have access to high-quality, and in some cases unique, experimental equipment and facilities. Geotechnical experts are working closely with engineering seismologists from the Southern California Earthquake Center (SCEC), private practice, and foreign entities. The thrust area researchers who are developing improved ground motion excitation scenarios, calibrated soil constitutive relationships, and soil-foundation-structure interaction models work closely with the OpenSees developers to add these geotechnical capabilities. Significant interaction with practitioners is also taking place through the testbed modeling efforts

2.4.4 TA 2 Research Advances and Deliverables

Hazard Assessment and Geo-Performance researchers continue to make significant advances in a number of important areas. Considerable progress has been made in developing improved understanding (and in modeling) of the medium- to large-strain behavior of liquefiable soils. This year, a new PEER website will incorporate the unique lateral deformation 1D and 2D shear-testing set of experiments funded earlier by PEER (Annie Kammerrer PhD Thesis work, Seed and Pestana advisors). Such studies are the basis for PBEE computational simulations where predication of deformations is of primary concern. The bridge testbeds have allowed an integrative environment where the geotechnical developments are now culminating in full 3D ground-bridge modeling efforts. In this context, nonlinear soil behavior, definition of seismic input motion, soil-foundation and soil-abutment interaction models are all at play (from the geotechnical side). Geotechnical uncertainties are also being directly addresses for site response as well as for the overall ground-bridge system.

The experimental shallow and deep foundation research is producing valuable data sets. Quantitative data of nonlinear soil-shallow foundation interaction and liquefaction response of pile systems are filling a void. These data are the basis for developing and validating simulation models in OpenSees.

The Lifelines Program is building on earlier source-site numerical calibration efforts, enhancing the Ground Motion Data website resource, and initiating the Next Generation Attenuation multi-investigator initiative.

2.4.5 TA 2 Future Plans

Year 7 research projects will further focus on SFSI, particularly, influence of foundation performance on structural performance (Kutter 226, Martin 227.1, Hutchinson 227.2, Boulanger 231, Stewart 239), and extension of the OpenSees geotechnical modeling capabilities. Much attention will be further directed towards rendering OpenSees an environment for routine advanced simulation, with integrated probabilistic analysis capabilities (Elgamal 220, Jeremic 221, Conte 413). PEER also intends to translate the SFSI research outcomes into performance-based design recommendations and guidelines, including plans for a workshop on deep foundations (Boulanger 237). It is envisioned that working groups in years 8 and 9 will define the appropriate scope, conduct the workshops, and compile milestone recommendation reports regarding this shallow and deep foundation research.

Related to SFSI for deep foundations, the influence of ground deformation and foundation behavior on structural performance will remain an important area of investigation (TBA 3G02, Boulanger 237, Ashford 234). Research to determine the effects of factors such as foundation yielding on structural performance will be conducted. This research will shed light on the benefits (e.g., reduced structural demands) and drawbacks (e.g., foundation settlement) of designing foundations to allow limited yielding. Additionally, this work is expected to lead into further efforts on applying soil improvement as a design parameter within PBEE. Ground improvement efforts will naturally be directed towards liquefaction and lateral spreading effects on foundations and bridge abutments.

In the hazard analysis area, researchers from TA 2 and TA 3 are continuing work to identify and probabilistically characterize hazard intensity measures that correlate well to both geotechnical and structural aspects of performance (Bray 238, Beck 335). Procedures for selection of hazard-consistent ground motion time histories will also be developed.

The OpenSees analytical platform will continue to play an increasing role in geo-performance research, and further development of its geotechnical modeling capabilities will be supported (Elgamal 220, Jeremic 221, Fenves 410). These capabilities include performing fully coupled analyses (solving the fully coupled deformation/flow problem) involving pore-water pressure redistribution and dissipation, the implementation of additional constitutive models, spatially variable input motions, as well as increased emphasis on three-dimensional soil-foundation-structure analyses when appropriate. Documentation to facilitate use of OpenSees by PEER researchers and others is a continuing emphasis.

In the Lifelines Program, work in hazard assessment and geo-performance will include practice oriented site response validation studies (Willis 1L05, Nigbor 2A02d, TBA 2B03, TBA 2G02, TBA 3D04) based on available recorded motions at a number of highly characterized soil sites. Further work is also anticipated related to uncertainties in measuring dynamic soil properties, so that reliability based models can appropriately account for the possible bias of particular testing methods. The Next Generation Attenuation (NGA) effort started this year will be augmented as needed with statistically based, numerically derived ground motions, with associated tools for including attenuation uncertainties (TBA 2M, TBA 1L07). Results of the NGA studies will lead to implications on current site amplification factors, and on developments of site-specific ground motions. In addition, the Lifelines Program is developing regional earthquake ground-deformation maps, with liquefaction mapping probabilistic estimates (TBA 3A05, TBA 3G03). This project will involve direct participation of state and federal agencies (California Geological Survey, and United States Geological Survey), with immediate practical applications. Other upcoming projects include validation of available liquefaction-induced lateral spreading models, and effects on foundations and bridge abutments.

2.5 Thrust Area 3 - Assessment and Design Methodologies

2.5.1 TA 3 Goals

This thrust area focuses on methodological developments and on integration of components of the methodology, as developed in other thrust areas, into the PEER PBEE framework. Road maps for methodology development are created in this thrust, gaps in presently available knowledge are identified and closed (or narrowed) to the extent feasible, and maturing aspects of the methodology are tested in testbeds and yet-to-be-developed benchmark problems.

This thrust area has its focused research agenda, but its function also is to coordinate and test knowledge and tools developed in all thrusts to serve the common global objective of providing

- a methodology that will facilitate decision-making by policy makers, planners, facility managers, and owners in regard to cost-effective risk management of the built environment in areas of high seismicity;
- a methodology that will facilitate the implementation of performance-based design and evaluation by the engineering profession; and

- a foundation on which code-writing bodies can base the development of transparent performance-based provisions.

The specific objective of research in this thrust area is to develop (a) a comprehensive reliability-based methodology for socio-economic and engineering performance assessment of structural, nonstructural, and content systems, and (b) performance-based design procedures that account explicitly for multiple performance objectives with respective acceptable risks or target reliabilities. The focus is on a systems approach, starting from the seismic hazard, considering the complete soil-foundation-structure system, and for buildings considering structural, nonstructural (e.g., architectural and mechanical), and contents systems.

Central to the research performed in this thrust area is the systematic consideration of the important uncertainties in every element of the problem, and of the propagation of uncertainties throughout the problem (from seismic hazard to response prediction to damage prediction to the evaluation of decision variables). Emphasis in research is on reducing epistemic uncertainties, establishing measures of uncertainties (epistemic and aleatory), and developing a methodology that accounts for these aspects in the design and evaluation process. The outcome, in terms of decision variables, is expressed in metrics that specifically address direct financial losses, downtime (or loss of function), and casualties (or in a simplified manner, collapse).

2.5.2 TA 3 Strategic Plan and Milestones

Figure 2.14 shows the strategic research plan for meeting the goals of the Assessment and Design Methodologies thrust area. The plan focuses on Years 6 to 10. It identifies integration milestones and topical issues that need to be addressed in order to achieve these milestones. The topical issues are separated (albeit they often serve more than one purpose) into four focal areas, ranging from performance assessment methodology to implementation.

The first five years of the program were devoted to the development of methods and concepts needed to formalize a reliability-based performance assessment and design process. The emphasis was on fundamental development for performance assessment. Starting in Year 5, issues of performance-based design, concept testing, benchmarking, packaging, and implementation are growing in emphasis. At the same time, work on insufficiently resolved issues of performance assessment, such as uncertainty quantification and propagation, casualty/injury evaluation, and *EDP-DM-DV* relationships, is continuing to receive attention.

At the end of Year 6 most basic concepts of a comprehensive performance assessment framework should be in place. For implementation, additional work needs to be done on the issues itemized in the previous paragraph. The importance of uncertainty quantification and propagation is fully recognized and is receiving much attention. Different methods for uncertainty propagation are being explored and evaluated, ranging from simple first-order, second-moment approaches to full Monte Carlo simulation. Work is being performed on quantifying sensitivities and identifying those uncertainties that significantly affect the decision variables on which performance assessment is based. Consideration is given, through a benchmarking effort, to various methods of seismic hazard and ground motion representation and their effect on *EDP* predictions.

Loss assessment is expected to remain the subject of research until at least the end of Year 8. In part, this research is performed in TA 1 in order to benefit more from direct interaction with researchers on the socio-economic aspects of performance assessment. In part, it is continued in

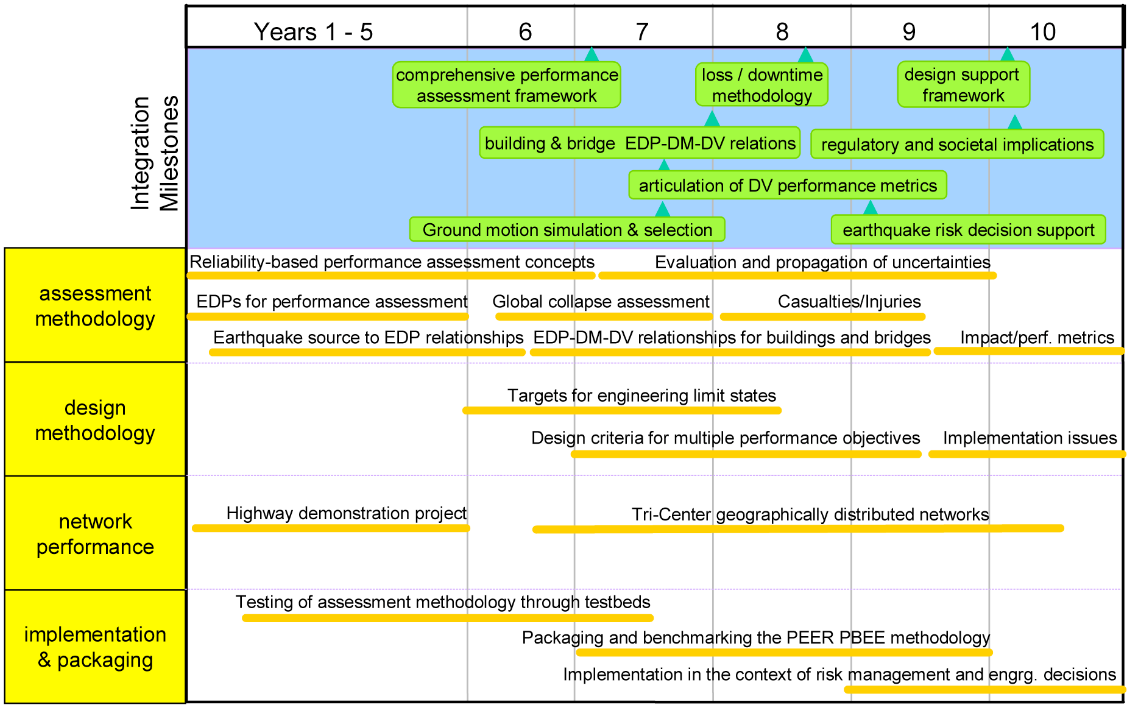


Fig. 2.14 Strategic Plan – TA 3 Assessment and Design Methodologies

this thrust, with an emphasis on modeling of the probability of collapse and of fragility curves for structural components, which relate engineering demand parameters (*EDP*s) to damage measures (*DM*s) and to decision variables (*DV*s).

Work is being performed on simplified approaches for performance assessment that can be employed readily in engineering practice. This work ties in with planned research on the establishment of targets for engineering limit states that can become the focus of performance-based design and for the development of design criteria for multiple performance objectives. In Years 9 and 10 much effort will be devoted to issues that will close the gap between fundamental research, which is a strength of the PEER community, and engineering implementation, which is a combined strength of PEER researchers and industry partners. We see great opportunities in working closely with the ATC-58 team that is charged with the development of performance-based seismic design considerations for engineering practice.

Testing of the performance assessment and design methodologies forms a crucial part of the development effort. For this purpose, two major efforts are in the research plan. One is the testbed program, which utilizes four testbed structures (two buildings and two bridges) that have become the center of focused studies in which the PBEE assessment methodology is tested, additional research needs are identified, simplified approaches are developed, and the socio-economic impact of different performance objective formulations is demonstrated. This effort will be completed in Year 7.

The second effort will be started in Year 7. It is concerned with packaging and benchmarking the PEER PBEE methodology for buildings and bridges. For buildings, this effort ties in with the needs of the community to carry out an assessment of the performance of buildings designed according to present code requirements. The plan is to select a small set of buildings, apply the PBEE methodology, and in the process find out how the methodology has to be packaged in order to be useful to the engineering profession. A similar effort is planned for highway bridges, which will be coordinated with the methodology development in TA 3 but managed through the research program for TA 5. Management of the bridge research through TA 5 is driven by three considerations: (1) the governing simulation and performance issues for RC bridges are more directly related to cumulative damage effects in bridge piers, which is an active topic of research in TA 5, (2) beginning Year 7, TA 5 researchers will begin investigating innovative systems and how the PEER PBEE methodology can be applied to demonstrate the enhanced performance enabled by these systems, and (3) balancing of effort and research specialties of the respective thrust leaders of TA 3 and TA 5.

Finally, another research area that falls under the general category of methodology development is associated with geographically distributed networks. As described in Section 2.2.3, one of the demonstration milestones completed in Year 6 was a demonstration project on the seismic performance of the San Francisco Bay Area Highway Systems. Beginning in Year 7, research on distributed systems will be expanded from the previous focus on transportation systems to also include electric utility systems, and the research will be coordinated through the new tri-center initiative of distributed networks. Details of the tri-center initiative are included in Volume III to this report; those projects related to the methodology and network aspects of the initiative are included here under TA 3.

2.5.3 TA 3 Critical Mass and Level of Effort

The research has focused and will continue to focus on the development of fundamentals for performance-based evaluation and design with due regard to uncertainties. Thus, expertise in probabilistic methods and reliability analysis is essential for this task. So is expertise in hazard analysis and in nonlinear behavior of structures. The research team has been put together to cover all these areas of expertise and to ensure close interaction with efforts in other thrust areas that are related to methodology development. The methodology development in TA 3 includes applications to buildings and bridges, and up through Year 6, projects on both were managed through TA 3. For the reasons noted above, beginning in Year 7, projects with a bridge focus will be managed through TA 5.

Considering both the core and Lifeline (LL) programs, the effort during Year 6 is focusing on the quantification of parameters and characterization of uncertainties in the *IM* and *EDP* domains (317, 318, 319, and LL507), issues related to collapse and life safety (319 and LL507), engineering approaches to performance assessment (319, LL507 and LL508), development of fragility curves that encompass the path from *IM*s to *EDP*s (and to some degree from *EDP*s to *DM*s) (318 and LL507), cost sensitivity (LL6D01), and testbed-specific projects (324, 325, 326, 327, 329, 332, and 333). Several of these projects are carried out by practicing engineers (329, 332, 333, LL508, LL6D01), who bring a much needed practice-oriented component to PEER's fundamental research. In addition, several of the seismic hazard and ground motion related LL project (1A03, 1C08, 1F01, 1G00, 1L01, 1L02, 1L06) provide much needed input to the ground motion representation issue that forms a fundamental part of the PBEE methodology.

2.5.4 TA 3 Research Advances and Deliverables

Basic formulations of the performance assessment methodology have essentially been completed, have been published in conference proceedings, and are being written up for journal publication. Specific accomplishments in the context of methodology have been the development of fragility curves for bridge bents (318), and of collapse fragility curves for deteriorating structural systems (319). Deteriorating hysteresis models have been developed, calibrated, and documented, whose implementation permits an assessment of the sensitivity of collapse to intensity and frequency characteristics of ground motions, and to strength, deformation, and ductility characteristics of the components that compose the structural system.

Work is in progress on gaps that have to be closed to allow implementation of the methodology, including further development of analytical tools, and establishment (in conjunction with TA5) of relationships between engineering demand parameters and associated damage and losses (fragility curves, cost functions). A comprehensive study has been completed on the evaluation of demand parameters for frame structures and their dependence on ground motions (319), which has resulted in a comprehensive database relating *EDP*s to *IM*s for ordinary (not near-fault) ground motions.

Work in part has been completed (Beck 122 and Porter 326) and in part is in progress (Kramer 235 and Krawinkler 319) on uncertainty propagation of ground motion and modeling parameters (including geotechnical parameters, Kramer 235), quantifying sensitivities and permitting isolation of important sources of uncertainty. This work utilized various methods, including tornado diagrams and first-order second-moment reliability approaches, with full Monte Carlo simulation being on the agenda for benchmarking of specific results. Work has been completed on a comprehensive formulation of a first-order second-moment scheme for conducting uncertainty propagation through the random vectors of *EDP*s and *DM*s to the *DV*s in the PEER framing equation. The results are the first and second moments of the *DV*s, given *IM*. These can be used with the *IM* hazard curve to produce mean and variance of each *DV* and mean annual probabilities of the *DVs.*

Much progress has been made on the four testbeds, which have become focal points for testing the PBEE methodology. For each testbed, sets of representative ground motion records at varying hazard levels have been generated and refined analytical models have been developed. For the Van Nuys building testbed (Lowes 327, Miranda 118, Heintz 329), emphasis is on the evaluation of losses due to structural and architectural damage, and on collapse safety evaluation. For these specific purposes, this testbed has become the main testing ground of the PEER methodology. For the UC Science building, *DM*s and *DV*s have been defined that are of interest for evaluating the seismic performance of the laboratories in the building (Mosalam 324, Beck 122). Shaking table tests of various laboratory equipment have been completed (Hutchinson 529, Makris 530), and fragility functions that relate *EDP* to *DM* have been generated. Work is now underway to utilize these fragility functions to perform damage and loss analyses of the facility, with an emphasis on contents damage (Beck 122, Comerio 120).

For the I880 bridge testbed, analytical models of various complexities have been developed (Kunnath 325, Imbsen 333), which are used to predict *EDP*s, which in turn are used in conjunction with fragility curves for various RC column damage states from (Eberhard 528) to perform damage predictions at the various hazard levels. In the Humbodt Bay bridge testbed study the emphasis is on refined analytical modeling with a focus on the effects on seismic performance of geotechnical issues, including soil liquefaction, approach fill settlement, and lateral spreading (Elgamal 220, Conte 413, Nascimento 332). Detailed simulation and performance studies are performed to evaluate (a) the impacts of permanent ground deformation on response of the bridge system; (b) the effectiveness of the seismic retrofit; and (c) the propagation and significance of uncertainties in earthquake source mechanisms, site and soil parameters, and foundation and structural response on the resulting performance metric.

2.5.5 TA 3 Future Plans

The Year 7 projects in this thrust area are intended to (a) address unresolved issues, (b) continue issues that need long-range attention, (c) start the process of in-depth testing and packaging of the PBEE methodology, or (d) support the tri-center distributed network initiative. The project by Beck (335) falls mostly in the first category. It will initiate a benchmark study in which two contrasting ways to represent seismic hazard and ground motions will be evaluated, one representing the approach explicitly incorporated in the PEER framework equation (based on an *IM* hazard curve and recorded ground motions), and the other based on source modeling and simulation of ground motions. This will be coordinated with hazard related research in TA 2 (Bray 238) and a continuing project on vector-based hazard models (Cornell 328). The issue of uncertainty propagation will be investigated further by Beck and Porter (122) together with the challenge of formalizing *EDP-DM-DV* relationships. Formalization and quantification of relationships of the latter type, for structural elements of reinforced concrete structures, are the subject of Lowes (342). Development of criteria for performance-based design will receive specific attention by Cornell (337), Krawinkler (338), and a Lifeline project (TBA LL509).

Testbed studies, which are ongoing commitments for many PIs, will continue for part of Year 7. This work requires significant coordination effort, which is funded through Porter (326). Major new efforts will be started on packaging and benchmarking the PEER PBEE methodology for buildings (Deierlein 334) and bridges (Stojadinovic 539), as summarized in Section 2.2.4.2. Finally, several projects will contribute to either coordination (Moehle 336) or specific research needs of the tri-center initiative (Kiremidjian 339, Moore 340, TBA LL602B and TBA LL603).

2.6 Thrust Area 4 - Simulation and Information Technologies

2.6.1 TA 4 Goals

New computational methods for simulating the performance of structural and geotechnical systems are needed for PEER's PBEE approach to determine engineering demand parameters for systems with highly nonlinear behavior and load redistribution caused by cyclic degradation and the consequences of local failure modes. Thrust Area 4 continues to focus on this development and, in the past year, has achieved increased integration in the computational and information technology areas:

- Soil-foundation-structure interaction, including deep foundations in liquefiable soil and new research on shallow foundations.
- Collaboration with seismologists and computer scientists to develop an integrated methodology for understanding the seismic performance of an urban region (SPUR).
- Component models for reinforced concrete with an initial examination of damage measures for performance evaluation.

- Simulation for reliability computation, including exact computation of response gradients for highly nonlinear systems.
- Database applications to support simulations for the testbed projects.
- Initiation of a new project on scientific visualization of structural and geotechnical simulations.

The PEER research program addresses the computational simulation needs for PBEE through a coordinated development of improved models of structural components (in this thrust area and TA5) and soils (TA2). The mechanics models are based on observed behavior of materials and components, and validated using databases of experimental data. The incorporation of uncertainty in the simulations is essential, and the research in this thrust area has resulted in important developments in the methods and software for reliability computation.

As described in Section 2.1.3, the OpenSees software has enabled research on simulation and provided a platform for PEER participants and others to conduct advanced simulations. The OpenSees framework uses object-oriented methodologies to maximize modularity and extensibility for implementing models for behavior, solution methods, and data processing and communication procedures. The framework is a collection of inter-related classes, such as domains (data structures), models, elements (which are hierarchical), solution algorithms, integrators, equation solvers, and databases. The classes are as independent as possible, which allows great flexibility in combining modules to solve simulation problems for buildings and bridges, including soil and soil-structure-foundation interaction, and most recently including reliability computational modules. The open source software is managed and made available to users and developers through the OpenSees website at http://opensees.berkeley.edu .

The development of OpenSees has been primarily motivated by the lack of adequate models and software to conduct research in PBEE using advanced information technology, including databases, visualization, and high-end computing. As an advanced platform for computational simulation, *OpenSees* provides an important resource for the National Science Foundation-sponsored George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). The modular design of *OpenSees* means that it can be customized for the integrating physical and computation simulation through data repositories, visualization, and hybrid control for advanced experimental methods, all of which meet important NEES objectives. With community support, *OpenSees* provides long-term opportunities that include: (i) use in NEES in a cycle of improving model-based simulation using data from advanced experimental facilities, (ii) extensions to include grid-based and other high-end computing for earthquake engineering, and (iii) integration with structural health monitoring systems using widely distributed MEMs sensors and processors.

2.6.2 TA 4 Strategic Research Plan, Milestones and Deliverables

Figure 2.15 shows the strategic research plan for TA 4, emphasizing Years 6 to 10 and identifying the system-level integration activities with milestone years and the five areas of thrust-level research. The first five years of the TA 4 were largely devoted to the development of new models and computational methods needed for structural and geotechnical simulation and implementation in the OpenSees software framework.

OpenSees is currently in Version 1.4, which is being used by researchers in the four testbed projects and other applications. The plan is to begin a new phase of the framework development

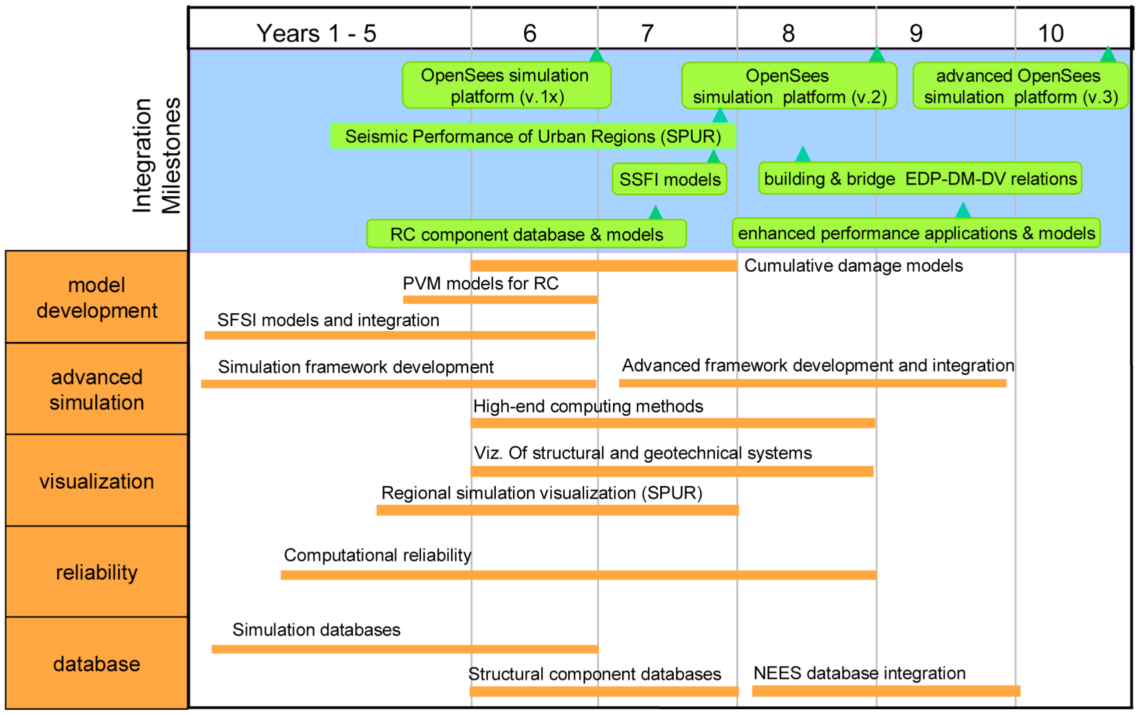


Fig. 2.15 Strategic Plan – TA 4 Simulation and Information Technologies

in Year 7, leading up to a new full release of Version 2.0 in Year 8, with interim releases between now and then. A feature list of Version 2.0 is under development, and it will likely include facilities and data structures for handling different types of unknowns (DOF), better support for regions and partitioning beyond what is currently available, improved handling of parameters and parameter sensitivity, and new features for parallel computing. These enhancements and new features will allow more sophisticated simulation for multi-physics problems, such a soil liquefaction, hybrid computational-experimental simulation, and high-end computing on parallel and distributed computers. This effort planned for Years 7 to 10 will increase use of OpenSees for NEES research within and beyond PEER.

In addition to research and development on advanced simulation, there are four other research focus areas in Thrust Area 4. Model development will continue with improved elements with shear-flexure-axial interaction for reinforced concrete members. This research will extend the new approaches to include the non-local (in the sense of sections) interactions with shear. Additional research is needed to develop improved models and calibrations for cumulative damage, including low-cycle fatigue, bar buckling, and fracture, and understanding how these behaviors are affected by loading history.

Visualization of simulations is important for understanding the complex responses that evolve in time during an earthquake. Research on visualization, including stereoscopic, will continue at the San Diego Supercomputer Center. A second project using immersive visualization (COVE) is being conducted with a collaborative project on seismic performance of urban regions (SPUR), as described in the next subsection.

Research on computational reliability methods based on simulation and exact computation of response derivatives has been underway for several years and will continue. Current research focuses on first-order methods and intelligent sampling for Monte Carlo simulation, with particular emphasis on degrading models and parallel systems to represent multiple failure modes. Future research will examine second-order methods.

The fifth thrust area focus is the development of databases for simulations and component behavior. The experimental databases provide searchable repositories for experiments on structural components. A similar database design is being developed in Project 2L02 (Archiving and Web Dissemination of Geotechnical Data). The data are used to validate the applicability of models and to calibrate specific models for a simulation. Validation of models incorporated into OpenSees is necessary to document the capabilities (and limitations) of models. A simulation database has been developed and tested in the testbed project. Future work will integrate the PEER databases into the NEES collaboratory.

2.6.3 Critical Mass and Level of Effort

The research team for Thrust Area 4 includes experts on modeling reinforced concrete components and simulation methods for such models. The researchers work with TA5 researchers in developing the models using experimental data. Other researchers in the thrust area are acknowledged leaders in the field of structural reliability. For development of the software framework, several of the thrust area researchers have computer science backgrounds and in many cases collaborate with computer scientists on research related to the simulation framework. As the simulation methods are being used in the bridge and building testbeds, PEER researchers and industry partners are providing feedback on the effectiveness of the research products in simulation and usefulness of the databases.

One of the weaknesses sited in the previous site visit review and report was inadequate support for information technology, computer science, and visualization. It should be noted that many of the graduate students conducting research in the thrust area are taking courses in computer science, generally as a minor program of study. This breadth of graduate education in computer science is unusual in earthquake engineering, and it has brought new technology and computer science methods into the PEER research program. Additionally, a number of thrust area researches have extensive experience in computer science and a track record of working with computer scientists. In the past year, two specific collaborations have been undertaken to provide computer science expertise. The first collaboration is with Dr. Michael Bailey of the San Diego Supercomputer Center in a new project on scientific visualization for structural and geotechnical systems. Bailey is looking at stereoscopic visualization methods and new ways to show stress, strain, and energy fields in continuum models for soils and frame models for structures. This project builds upon initial work of Bailey on structural systems (with Fenves) and soil systems (with Elgamal).

A second major collaboration is with computer scientists through a separate collaborative NSF-sponsored project on Seismic Performance of Urban Regions (SPUR), which is allied with the PEER research program. This project integrates PEER's research on structural and geotechnical simulation with fault rupture and ground motion simulation of a region (by Bielak at Carnegie Mellon University) and system integration and visualization research by computer scientists at Mississippi State University and University of California, Irvine. Computer scientists at MSU (Haupt) are developing middle-ware for communication of massive amounts of data between databases and OpenSees, ground motion simulators, and visualization tools. Computer scientists at UC Irvine (Meyer) are developing new rendering methods that can handle scalable visualizations of the subsurface, ground surface, and buildings in a region during an earthquake. Meyer is developing portable visualization for immersive systems (such as the COVE) and standard graphics boards and displays.

Thrust Area 4 works closely with other researchers in PEER, particularly in Thrust Areas 2, 3, and 5. To support the OpenSees software development and usage, research engineers and post-doctoral researchers provided a necessary continuity of expertise. Thrust Area 4 has two research engineers (McKenna and Mazzoni) and one post-doctoral researcher (Peng), and they coordinate with two-post doctoral researchers in Thrust Area 2 on the geotechnical models and simulation methods.

2.6.4 Research Advances and Deliverables

In the past year, significant effort in the thrust area has been devoted to the support of the simulations in the testbed projects and validation of the OpenSees models. The support entailed the following activities: (a) training of students and researchers on OpenSees; (b) improvement of OpenSees user documentation; (c) assistance with development of models and scripts; (d) responding to bug reports and technical assistance; and (e) review and feedback of experience with OpenSees models, facilities, and computational efficiency.

Thrust Area 4 researchers worked closely with the Humboldt Bay bridge testbed team on the models and simulations for SFSI (Conte, 413, and related development by Elgamal, 220). The robust solution methods in OpenSees were particularly valuable because of the complexity of the soil models for liquefaction. The other bridge testbed on the I-880 viaduct (Kunnath, 325) used the nonlinear beam-column models, including a validation study, and the soil-foundation-structure interaction models developed in Thrust Area 2. The building testbed project on the Van Nuys building (Lowes, 327) used the shear models in the nonlinear beam-column elements and a recently implemented RC joint model (Deierlein 412). The OpenSees scripting facilities allowed parameterization of the models for a large number of cases. The fourth testbed project on the UC Science building (Mosalam, 324) conducted extensive analyses of the building for floor acceleration records used in the shaking table and analytical studies of non-structural component performance.

In two other collaborative application studies, OpenSees models are being evaluated against test data from large scale experiments. In one case, soil continuum models for simulating ground deformations are being evaluated against a large-scale test in Japan, where explosives were used to trigger liquefaction in a test field containing pile foundations and a buried pipe (Ashford 234). In the second case, OpenSees frame models are being validated against a full-scale pseudo-dynamic frame test, results of which are made available through collaboration with the National Center for Research in Earthquake Engineering (NCREE) in Taiwan (Deierlein 420).

Apart from the model and simulation capabilities utilized for the testbeds, the very large and complex data demands of the Humboldt Bay testbed utilized a new distributed database module (by Law 415). The database was implemented on a widely available DBMS, MySQL, using standard SQL API communicating with the OpenSees API. The database allows users to catalog all models and simulations for a model to conduct post-processing across the models and simulations.

Year 6 has seen the completion of a number of efforts for the models and computational features of OpenSees. A range of hierarchical models for beam-column elements is now available, including flexure, axial, and shear effects (Fenves and Filippou, 410) and generalized hinges (Deierlein, 412). The models include material and component behavior for cyclic degradation and large-displacement analysis. To support reliability and other applications, a new efficient algorithm for computing the response sensitivity for force-based elements has been developed and implemented (Fenves and Filippou 410). To solve large-scale systems with degrading components, a new quasi-Newton solution method based on a Krylov subspace has proven to be very efficient and robust when used in the testbed projects.

Continued progress has been made with integrating reliability computation into OpenSees. Der Kiureghian (414) has extended the first-order reliability method, many of the element and material models now support direct differentiation for computing response sensitivities for reliability computation. The research has also made progress on importance sampling for Monte Carlo simulations and extending a library of distributions and correlation structures for random variables. Conte (413) has been using these methods to begin probabilistic evaluation of the Humboldt Bay bridge with the completion of a complete model of the SFSI system. Progress on these projects responds to concerns raised in previous years' site visit reports about the need for reliability tools in OpenSees, which facilitate application of the PEER PBEE methodology and are not generally available in other earthquake analysis software.

2.6.5 Future Plans

Support and continued development for OpenSees will continue as a high priority, given the central role OpenSees plays as an enabling technology in PEER. During Year 7, development of Version 2.0 will commence and efforts to grow and support the expanding user/developer base will continue. Most of this support is through the core development staff of research engineers at Berkeley (Fenves 410).

Model development will continue with advanced shear-flexure-axial interaction models (Filippou 421), cyclic degradation models (Kunnath 423) and coordination with model development projects in Thrust Areas 2, 3, and 5 (Elgamal 220, Jeremic 221, Kutter 226, Hutchinson 227, Boulanger 231, Deierlein 334, Lehman 540). A Year 6 project on shear walls (Wallace 533), including shear-flexure interaction, will provide a necessary tool for simulation of performance of a many reinforced concrete buildings (as recommended by our Scientific Advisory Committee and Implementation Advisory Board). In Year 7, projects are continuing the development of computational reliability methods and the broadening applications for non-ductile systems with multiple failure modes (Der Kiureghian 414, Conte 412). Visualization research with computer scientists at SDSC will provide a valuable tool for helping with new insights about structural and geotechnical performance simulations (Bailey 418). Finally, Year 7 will see the first level of integration of PEER simulation research with NEES by using OpenSees as a computational tool driver for hybrid testing and high-performance computing (Mahin 419, Fenves 422).

2.7 Thrust Area 5 - Structural and Nonstructural Performance

2.7.1 TA 5 Goals

The primary goal of Thrust Area 5 is to develop the fundamental knowledge and understanding of the performance of structural and nonstructural components, equipment, and systems (including uncertainty and randomness) needed to develop computational tools for simulating performance of buildings and bridges. Performance characterization includes conventional representations such as strength and deformation capacity, and also includes damage parameters related to functionality and repair/restoration. Research efforts in this thrust area include:

- Review, synthesis and evaluation of prior work related to specific aspects of structural and non-structural component performance,
- Identification of robust parameters for characterizing and quantifying performance and of structural and nonstructural components and systems,
- Development of conceptual and theoretical models to evaluate the performance of structural and nonstructural elements as well as complete systems, and
- Conduct tests and analyses, as necessary, to provide data needed to fill essential knowledge gaps as well as to assess computational tools and models being developed in other thrust areas.

Activities in TA 5 are integrated with projects and research needs of other areas. Close coordination with TA 3 concerns the establishment of definitions and performance data to relate *EDPs* to *DMs* for structural and nonstructural components, in a manner consistent with the overall PBEE evaluation and design methodology. During Years 5 and 6, this included close cooperation to develop *EDP-DM-DV* relationships for the methodology testbeds, particularly with regard to laboratory equipment testing for the UC Science Building. Beginning in Year 7, consideration of system aspects will increase as TA 5 assumes a larger role in assessing the overall performance of bridge systems, including exploration into innovative ways to enhance bridge performance. Collaboration with TA 4 relates most to the development, calibration, and validation of simulation and performance models for structural components and systems. Component level tests performed in prior years are now being extended through tests and analyses of more complex systems subjected to dynamic loading.

2.7.2 TA 5 Strategic Plan

The research plan for Thrust Area 5 is shown in Figure 2.16, where the detailed research plan is distinguished among the following four focus areas: (1) nonstructural components and contents, (2) building components and systems, (3) bridge components and systems, and (4) damage models. This organization represents an evolution from past years in that there is a more deliberate distinction between research directed towards structural components and systems for buildings and bridges. Additionally, as modeling methods become more sophisticated and focused on the *EDP-DM-DV* relationships, the topic of damage models (cumulative effects, low-cycle fatigue) takes on larger importance.

The Integration Milestones at the top of Figure 2.16 (and cross-referenced with the overall research plan and other thrust areas in Figure 2.11) follow directly from to goals for TA 5. The three lower-most milestones concern the development of data and models for structural

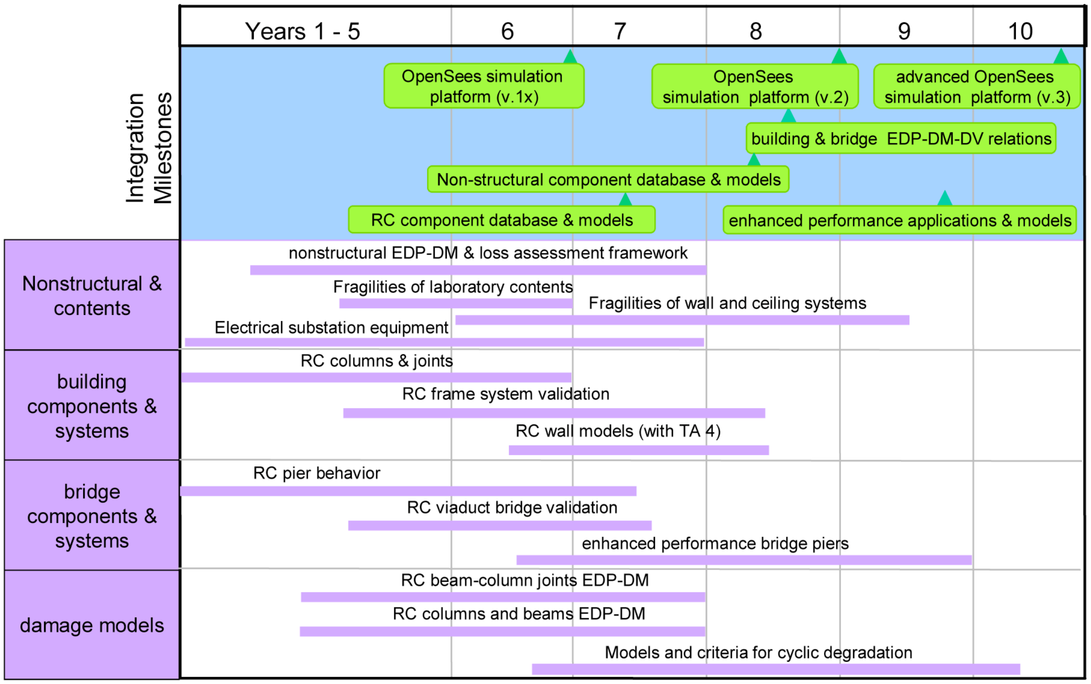


Fig. 2.16 Strategic Plan – TA 5 Structural and Nonstructural Performance

components, nonstructural components, and enhanced system components. As described below, the first planned application for enhanced system components involves study of self-centering post-tensioned bridge piers. Moving upwards through the integrative milestones, the next milestone concerns the development of performance (or "fragility") equations describing *EDP-DM-DV* relationships for bridges and buildings. Finally, the models and data developed in TA 5 ultimately contribute to development of the OpenSees platform.

Nonstructural Components and Contents: Ten projects are currently underway in Year 6 related to nonstructural components and contents. Two projects (Miranda 524 and Porter 537) relate to overall methodology development for architectural and mechanical/electrical components, with the objectives to develop a taxonomy by which to categorize standard building components, develop functional and economic loss models for these elements, and evaluate system performance dependency on the nonstructural components. Two other projects, begun in Year 5 and due to wrap up early in Year 7, are investigating the performance of laboratory building contents through shake table tests of laboratory equipment (Hutchinson 529 and Makris 530). These projects were initiated during planning for the UC Science building testbed in response to a loss assessment study (Comerio 120), which showed the major impact of potential losses due to damage of laboratory equipment and contents. Another experimental testing project was initiated in Year 6 to evaluate the performance of architectural gypsum-board partition walls (Filiatrault 532), which are a very common source of earthquake damage and losses. Apart from developing useful data, part of the rationale for the equipment and wall tests is to provide "best practice" examples on how to set up and collect relevant performance data for building components and contents. Five other projects supported by the Lifelines Program (Der Kiureghian LL 401b, Filiatrault LL402, Pardoen LL404, Fenves LL 411, and Ostrom LL 413) are underway to characterize the performance of electric substation equipment and facilities. Through the tri-center initiative on geographically distributed lifeline systems, plans are underway to collect and synthesize data from these component tests as input to fragility models for seismic risk assessment of electric utility systems.

Building Components and Systems: Past research on structural building components focused on "nonductile" concrete buildings, which are representative of older existing buildings that represent significant safety risks. Research in Years 1 through 5 focused primarily on capacity assessment of components and simple sub-assemblages for which inadequate quantitative information was available to support the development of simulation models or theoretical models for performance assessment. Previous research included quasi-static cyclic testing of shear-critical columns, column splices and column-to-footing connections, beam-to-column connections, flat-plate-to-column connections, and pile-to-pile-cap connections. In Years 5 and 6, the emphasis has been on generalizing the test results to develop simulation models for these elements (Eberhard 528, Lehman 535, Moehle 525) and to conduct a shaking table test to validate RC building system models (Moehle 525). A related project initiated in Year 6 will utilize existing test data to develop simulation models for RC shear walls (Wallace 533).

Bridge Components and Systems: Previously, a variety of tests have been carried out on modern, spirally reinforced column specimens to assess effects of loading history, loading rate, and variation of axial load. During Year 6, shake table tests have been run on single and multiple bents representative of bridge viaducts with varying degrees of indeterminacy and inelastic force redistribution (Mahin 527). Continuing studies are underway to compare the measured response and simulated response using OpenSees models. Two new projects initiated in Year 6 are investigating methods to apply vertical post-tensioning to enhance the seismic performance of bridge piers (Mahin 532, Billington 536). These studies are motivated by the observation that post-earthquake residual displacements are one of the primary contributors to bridge closure and replacement. The objective of the investigations is to show how post-tensioning, combined with mild steel reinforcement, can reduce residual drifts. These investigations will show how the PEER PBEE methodology can be applied to demonstrate the merits of a new system, and they will begin addressing questions of performance-based design – as distinct from assessment.

Damage Models: During Years 5 and 6, efforts have intensified to systematically archive data from column and beam-column joint tests and to generalize the results through damage (fragility) models. An electronic on-line database of column tests has been developed and is being used to develop and validate fragility relationships between *EDPs (*such as column ductility ratios, plastic hinge rotations, and strains) to damage states and implications on repair and safety (Eberhard 528). In Year 7, more emphasis and resources will be devoted to testing and model development for capturing damage accumulation under arbitrary earthquake loading.

2.7.3 TA 5 Critical Mass and Level of Effort

The research team for TA 5 includes experts in experimental and numerical analysis of structural and nonstructural components and systems. Most of the investigators have been extensively involved in post-earthquake reconnaissance; and they have considerable previous experience with the type of components and systems being investigated, so that the work being undertaken by PEER benefits substantially by leveraging this prior knowledge. The TA 5 research is directly related to information needed to develop and assess the OpenSees analytical platform and the structural and nonstructural models being developed. In addition, critically needed quantitative information on performance-oriented damage measures (e.g., defining the onset of permanent cracking, spalling, and bar buckling) is being compiled and used to develop/calibrate fragility models.

2.7.4 TA 5 Research Advances and Deliverables

The research advances and deliverables in TA 5 are the following:

- *Conforming RC Bridge Columns*: Extensive static, pseudo-dynamic, and shake table testing has provided data to improve understanding and models of loading history and loading rate effects (associated with near-fault pulse type loading). Data collected from these tests and previously studies have been assembled in an on-line performance database, which provides visual and numerical data relating engineering demand parameters, such as inelastic drift and curvature ratios to damage measures and repair techniques.
- *Non-conforming RC Building Columns:* Tests of reinforced concrete building columns with non-conforming details (shear critical, inadequate confinement, weak splices) have been conducted and used to develop improved models to characterize critical modes of failure. These data have been used to develop simulation/performance models in OpenSees.
- *RC Beam/Slab to Column Joints:* Tests have been conducted to develop improved strength equations and response models for non-conforming beam-column joints and slab-column joints. Data from these tests have been used to calibrate OpenSees models, and ongoing work is developing relationships between joint response and damage/repair models.
- *Nonstructural Components:* Fragility models for nonstructural components and laboratory equipment have been developed and applied in seismic loss studies of the two testbed buildings. Efforts are continuing to develop systematic and consistent approaches to characterize seismic performance in terms of *EDP-DM-DV* fragility relationships.
- *Substation Equipment:* Tests of electric substation equipment (transformer bushings, bus connectors, anchorages) have led to improved understanding of their response to seismic loads. Developed in coordination with the utility industry, these tests have resulted in design changes and repair strategies for electrical equipment. Fragility data from these tests are beginning to be incorporated in seismic risk assessment of electric utility systems.

2.7.5 TA 5 Future Plans

Plans for Year 7 follow along the four topic areas discussed above. In the area of nonstructural components, research will continue to collect data and develop methodologies for seismic performance and fragilities of components and equipment (Miranda 524, TBA LL414) and testing of architectural partitions (Filiatrault 532). Additionally, a new project is planned to characterize the performance of office building ceiling assemblies, including integral HVAC, electrical, and sprinkler systems (TBA 538). Research on RC buildings will continue with large-scale tests for validation of simulation and performance models (Moehle 525), which will feed into related OpenSees model development in TA 4 (Filippou 421) and RC building benchmark studies in TA 3 (Deierlein 334, Lowes 342). Work on bridge components and systems will emphasize the new focus on performance enhancement through post-tensioning (Mahin 534, Billington 536) and research on bridge system performance assessment (Stojadinovic 539). The latter project will be coordinated with bridge fragility modeling for highway network research in the tri-center program. Research on damage models will focus on calibration of *EDP-DM* relationships for columns (Eberhard 528) and a new focus on cumulative damage associated with low-cycle fatigue buckling and fracture of longitudinal reinforcement. The cumulative damage research will include testing and model development in TA 5 (Lehman 535) and computational implementations in TA 4 (Kunnath 423).

2.8 Research Management Committees and Personnel

The PEER research program is jointly administered by two committees: the *Research Committee,* which has primary responsibility for managing the *Core Research Program,* and the *Joint Management Committee*, which has primary responsibility for the *Lifelines Research Program*.

The *Research Committee* is chaired by Gregory Deierlein, *Deputy Director for Research*, who is a professor of Structural Engineering at Stanford University. Thrust Area 1, *Loss Modeling and Decision-Making*, is led by Professors Mary Comerio (Architecture, U.C. Berkeley) and Peter J. May (Political Science, Univ. of Washington). Comerio leads PEER research concerning damage evaluation, and Professor May leads PEER research concerning decision considerations for PBEE and adoption and implementation of PBEE. Thrust Area 2, *Hazard Assessment and Geo-Performance*, is led by Professor Ahmed Elgamal (Geotechnical Engineering, UCSD), who assumed leadership of TA 2 when Professor Steve Kramer stepped down at the end of Year 4. Professor Helmut Krawinkler (Structural Engineering, Stanford) is the leader for Thrust Area 3, *Assessment and Design Methodologies*. Professor Gregory L. Fenves (Structural Engineering, UCB) is the leader for Thrust Area 4, *Simulation and Information Technologies*, which is the thrust group leading the OpenSees development effort. Professor Stephen A. Mahin is the leader for Thrust Area 5, *Structural and Non-structural Performance*.

The *Lifelines Program* contractual agreements require a close coordination among the researchers and sponsors. To meet those requirements, PEER has established a series of Topic Area Leaders to provide close oversight and coordination of those projects funded through the Lifelines program. Being affiliated with the Business and Industry Partners, these topic leaders provide a natural technology transfer mechanism with the sponsoring organizations. Director Moehle works directly with Dr. Michael Riemer, *Program Manager for the PEER Lifelines Program* to provide overall coordination of the program. (Professor Fenves, who formerly served as the Assistant Director for the Lifelines Program, was relieved of this task when he became Chair of the Department of Civil and Environmental Engineering in 2002.) Topic Leaders are as follows: *Earthquake Ground Motion*, Dr. Norman Abrahamson (Seismologist, PG&E) and Dr. Brian Chiou (Seismologist, Caltrans); *Site Response*, Dr. Clifford Roblee (Geotechnical Engineering, Caltrans); *Permanent Ground Deformation*, Mr. Thomas Shantz (Geotechnical Engineering, Caltrans); *Electric Substation Equipment Vulnerability,* Mr. Eric Fujisaki (Structural Engineering., PG&E); *Electric System Building Vulnerability,* Mr. Kent Ferre (Structural Engineering, PG&E); *Network System Seismic Risk*, Dr. Stuart Nishenko (Seismology, PG&E). These topics are coordinated through the associated thrust areas.

3. EDUCATION PROGRAM

3.1 Strategic Education Plan, Methodologies, Milestones, and Deliverables

The Education Program is designed 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 career and aims to retain them through graduate study. While the principal audience of the Education Program is undergraduate and graduate students, K-12 students also benefit directly from the Education Program's activity. PEER's Education Committee, composed of representatives from all 18 core and affiliated universities, is charged with the planning and implement in the program.

Several specific programs have been instituted to provide undergraduate and graduate students with opportunities in the Education Program. Our overall objective is to build a culture within PEER, starting at K-12 and extending through graduate school, where students are excited about earthquake engineering learning and realize the need to contribute to the learning of others. Figure 3.1 illustrates the overall strategic plan with focus areas and milestones. Programs and deliverables cover the range from K-12, undergraduate students, and graduate students. Detailed descriptions of programs/projects are provided in subsequent sections of this chapter.

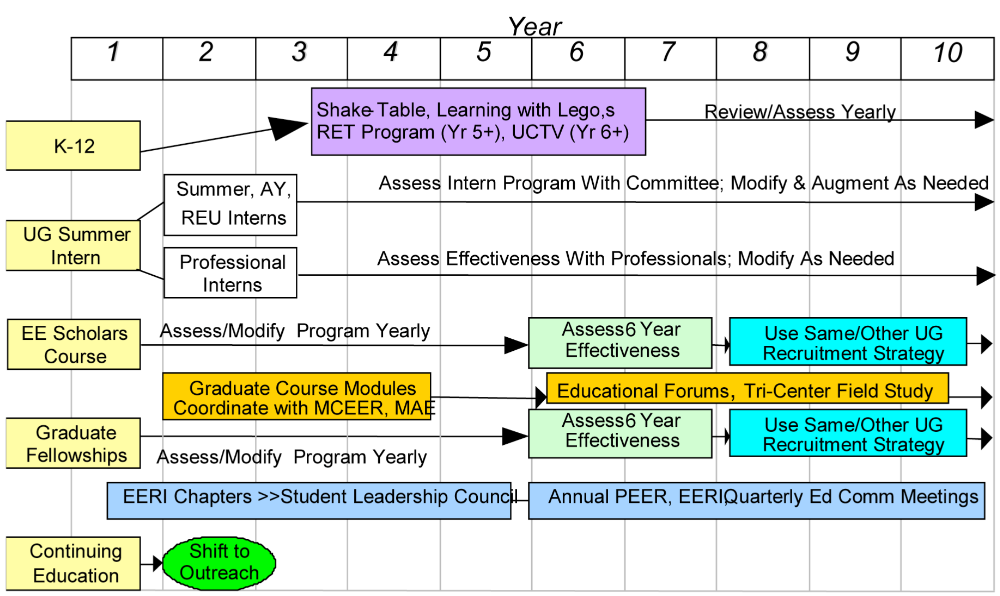


Figure 3.1 – Education Program Strategic Plan

3.2 Current Education Projects and Curriculum Innovations

3.2.1 Current Education Projects

During Year 6, the Education Program will sponsor eleven on-going projects. These are described briefly below:

3.2.1.1 Research Experience for Teachers (RET)

Middle school students from the inner city are often unaware of career opportunities in science and engineering. In an effort to improve math and science education at the middle-school level, PEER has begun working with teachers and their students through a ***Research Experience for Teachers (RET)*** supplemental grant. Our goal is to increase the knowledge and skill level of teachers from inner city schools, while at the same time having some direct impact on their students. This past year, nine teachers from eight inner-city schools spent several weekends on a PEER campus learning about earthquake engineering from faculty and graduate students, as well as receiving detailed instruction on operation of the university's laboratory equipment. These teachers then worked with their own students to develop science fair projects with experiments carried out by the students and teachers at the PEER university campus. Two of these projects have made it to countywide science fair finals, taking second place. We believe that this program is making an impact on K-12 education in two ways: (1) by developing earthquake engineering knowledge and laboratory skills of the K-12 teachers that they can utilize in the classroom, and (2) by exposing K-12 students to the university environment so that they can begin to realize it is an achievable goal for them.

3.2.1.2 PEER Summer Internship Program

The ***PEER Summer Internship Program*** is intended to interest, attract, train and retain promising undergraduates who have expressed an interest in earthquake engineering research. Students work, over a period of ten weeks, under the direction of a PEER faculty mentor on a PEER-funded research project during the summer months and submit a report detailing their research experience during the fall term. We endeavor to restrict interns to working on projects that are current or recent-past PEER projects, although in exceptional cases we will accept students to work on PEER-related projects. During the past four years, PEER sponsored participating students to attend the EERI Annual Meetings in St. Louis, Monterey, Long Beach, and Portland. Prior to the Friday evening reception, students presented posters about their summer research experience in an informal setting, while interacting with renowned specialists in earthquake engineering. PEER's internship opportunities provide students with experience in hands-on, individualized laboratory and field research, and increase opportunities in academia and professional practice. The students who participated in the PEER Summer Internship Program during summer 2002 submitted their final research reports on November 1, 2002. The interns' papers are being compiled into a compendium document for

Figure 3.2 - Participants in the 2002 REU Symposium

distribution to PEER's community of faculty and students. The Education Program is currently recruiting fifteen students to participate in the PEER Summer Internship Program during summer 2003.

3.2.1.3 Research Experience for Undergraduates Summer Internship Program

In a program that parallels the PEER Summer Internship Program, the ***Research Experience for Undergraduates (REU) Summer Internship Program*** sponsors PEER students working at an institution other than their home campus, or students from campuses outside the PEER consortium, to work on PEER-funded research projects mentored by a PEER faculty member. In addition to the research experience, the REU Program (in an activity conducted jointly with SCEC) offers a one-day Communication Skills Workshop for the interns to assist them with oral and written reporting skills. The Workshop affords them the opportunity to discuss their ongoing research experience with other engineering and earth science students. The impact of the workshop is evident in the superior quality of the REU students' oral presentations and written reports submitted during the fall term following their internship.

The REU program also provides an opportunity to meet REU students from the other EERCs and thereby learn how earthquake engineering is perceived in other parts of the US. In August 2002, REU students from MAE, MCEER, and PEER met in Keystone, CO for a lively discussion of ethics in engineering, as well as an opportunity to hone their presentation skills in PowerPoint presentations relating their summer research experience to the group.

The PEER Education Program is currently recruiting seven students, focusing on those from groups historically underrepresented in the field, for the summer 2003 REU Program. The 2003 REU Symposium will be held August 7-10 in Bend, OR.

3.2.1.4 Earthquake Engineering Scholars Course

PEER's Undergraduate ***Earthquake Engineering Scholars Course*** (EESC) is a program implemented to showcase the graduate programs at PEER core institutions and introduce high-ranked undergraduate students to four topics in the field of earthquake engineering including seismology, geotechnical engineering, structural dynamics, and public policy. The Fall 2002 version of the EESC was a multi-campus program that provided instruction to 30 students from eleven PEER universities during four weekend retreats at PEER core-university campuses (UC Irvine – Seismology; UC Berkeley - Structural Dynamics; UC San Diego - Geotechnical Earthquake Engineering; and UC Los Angeles - Public Policy). These individual topics were the primary focus of each of the four weekends; however, the students commented on the faculty's success in developing a connection between the four topics which united the course overall and provided the students an opportunity to explore many facets of the earthquake engineering profession. As an addition to the 2002 program, the Education Committee invited at least one PEER Business and Industry Partner member to present during each of the retreats. For example, at UC Berkeley, several young BIP engineers gave the PEER Scholars tours of seismic retrofit projects on the Berkeley campus, described engineering drawings and engineering

Figure 3.3 – PEER Scholars review structural drawings with SGH engineer Nathan Ingraffea

practices, and shared experiences going from school to professional practice. The schools also utilized the opportunity to conduct tours and "show off" their laboratories and facilities. An objective of the course is to recruit new talent to the field of earthquake engineering. Most students who participated in the EESC in 2000 and 2001 have gone on to pursue graduate study at a PEER institution.

The Education Committee has enthusiastically endorsed another Scholars' Course offering for Fall 2003. Retreats will be held at USC (Geotechnical Earthquake Engineering), Stanford (Seismology), University of Washington (Structural Dynamics), and UC Davis (Public Policy). As an addition to this year's program, each host university will invite a faculty member from at least one other PEER core school so that all core schools are represented.

3.2.1.5 Tri-center Earthquake Field Study Program for Students

The ***Tri-center Earthquake Field Study Program for Students*** is a new effort focusing on earthquake reconnaissance experience for PEER students starting in May 2002. Each summer this project brings students from MAE, MCEER, and PEER together to conduct post-earthquake investigations during a weeklong summer camp at a non-US site. The "new blood and experience" that are gained not only broaden the students' experiences but also train students future earthquake reconnaissance in programs such as the EERI Learning from Earthquakes Program. The participating students are drawn from a variety of institutions and disciplines. Each student is required to issue a formal reconnaissance report following the field investigation. The Education Directors have extended an invitation to EERI to fund four (non-EERC) students, plus a young faculty member, as part of its endowment program. In May 2002, three PEER students took part in the Taiwan Earthquake Field Study. In May 2003, three PEER students are scheduled to join their counterparts from MAE and MCEER for a field study in Italy. Students from the Southern California Earthquake Center (SCEC) will also participate. As this is a new program for PEER, the Education Program plans to conduct a critical evaluation of the program's value after the students submit their final reports in 2003.

3.2.1.6 Graduate Fellowship Program

Graduate student participation in PEER's research program is a traditional mechanism to train and educate students. To augment this traditional approach, the Education Program initiated the ***Graduate Fellowship Program*** as a way to recruit and retain graduate Ph.D. students from groups that traditionally have been under-represented in the profession. The program aggressively recruited students from various ethnic groups, and subsequently provided funding for $20,000 per year for up to three Ph.D. students to study at a PEER institution, contingent on the student remaining in good standing. The Education Committee reviewed this program over the past two years and has determined that it neither an effective nor viable means of recruiting students from under-represented groups into the PEER circle. Currently there is one student remaining in the program, with two others graduated with their Ph.D.s in Year 6. After this final student graduates in Year 7, the PEER Education Committee will shift funding to programs that will impact more students.

3.2.1.7 Student Leadership Council

PEER aims to create an environment in which students learn leadership and management skills through independent student organizations. In PEER's first years, we encouraged formation of EERI Student Chapters, with chapters now located at Caltech, Oregon State, San Jose State, Stanford, UC Berkeley, UC Davis, UC Irvine, UC San Diego, and the University of Washington. Starting in Year 2, PEER formed its ***Student Leadership Council*** (SLC) and ***PEER Student Association*** (PSA). Both undergraduate and graduate student representatives on the SLC, from the core and affiliated campuses, provide an active and valuable voice for all PEER students. Over the past four years, PEER's SLC has been an influential contributor to the PEER Education Committee and PEER Administration concerning the needs of undergraduate and graduate students. The SLC president attends each of the Education Committee's quarterly meetings to provide feedback and input concerning the programs offered by PEER Education. The SLC conducts its own quarterly meetings, which are scheduled to coincide with other PEER Research and Education events to maximize opportunities for networking and discussion. PEER's fourth Student Day, held concurrently with the PEER Annual Meeting in March 2003, was an excellent forum for students to share their intellectual and personal experiences as participants in the PEER. The event includes meetings of the SLC and other students, formal poster sessions, and presentations by PEER students and Business and Industry Partners.

3.2.1.8 Tri-Center Ph.D. Candidate Exchange

The ***Tri-Center Doctoral Candidate Exchange*** is a new program in Year 6 that will send two PEER graduates students nearing completion of their doctorate to give lectures at MAE and MCEER, while PEER will welcome to two students for lectures from each of these centers as well. The first exchange to PEER from MAE is scheduled for 5 May 5 2003, when Leonardo Duenas-Osorio from Georgia Institute of Technology with present the results of his MAE-funded research to a group of graduate students at UC San Diego. The program provides valuable speaking opportunities for advanced students and exposes research among the three centers in ways that would not otherwise occur.

3.2.1.9 PEER Lecture Series

In Year 6 PEER will also institute a ***PEER Lecture Series*** by key PEER Researchers and Business and Industry Partners. The lectures will be web cast to all PEER Core and Affiliate School, providing further linkage among the schools and ensuring that key research results/topical areas are widely shared within PEER. The first lecture will be offered by PEER Director Jack Moehle in Spring 2003.

3.2.1.10 Learning with LEGO Program

The ***Learning with LEGO Program*** was inspired by a campus initiative at UC Irvine that brought over 800 K-12 students from socio-economically disadvantaged areas to the campus for an open house and shake-table demonstration in Spring 2000. One might think that seismic simulation is a topic only for advanced graduate students, but it has caught the attention of these younger students as well. The event pitted local elementary, middle and high schools against one another for the honor of having the best seismic designs. The LEGO structures were tested on one of PEER's major earthquake simulators housed in the UCI Structural Engineering Test Hall. The event has been repeated each year, currently under the leadership of Tara Hutchinson, PEER Education Committee

Figure 3.4 – K-12 students eagerly await the LEGO-quake

member from UC Irvine. The Education Committee is considering expanding this effort to other PEER campuses.

3.2.1.11 PEER Professional Fellowship Program

The ***PEER Professional Fellowship Program*** is aimed at increasing contacts between our students and practicing professionals. Though started on an informal basis, our first formal PEER Professional Fellow was Maury Power of Geomatrix Consultants in 2002. Another of our Professional Fellows for Year 6 is William Holmes of Rutherford & Chekene, who on 14 May 2003 will give a lecture on "Staying Active in the Profession after Graduation." In addition to the lecture, Mr. Holmes will have lunch with members of the EERI Student Chapter and meet with graduate students to discuss their research. As a leading practitioner who is very involved in PEER, EERC, and code committee development, Mr. Holmes will be a superb role model for our PEER students. The Education Committee has been tasked with continuing to develop this program so that more students can gain this valuable exposure.

3.2.2 Curriculum Innovations and Tools

PEER has encouraged and coordinated several curriculum development activities, including the following.

3.2.2.1 Teaching Modules for Graduate Students

Initiated as a Tri-Center activity, this project has created a series of graduate-level, self-contained, web-based, teaching modules. The modules include materials on various subjects and may be shared by a variety of academic institutions that do not have resident expertise in specialized subjects pertaining to earthquake engineering. The modules consist of written text, specifications for experiments, visual materials and supplementary web information. Modules have been commissioned for the following areas: *Fluid Structure Interaction, Wave Propagation, Earthquake Engineering Design, Seismic Ground Motion and Hazard, Seismic Upgrading: A PBE Case Study, Seismic Behavior of Timber Structures*, *Earthquake Resistant Design*, *Liquefaction*, *Socioeconomic Aspects of Earthquakes, Putting a Face on Earthquakes: The Human Side of Earthquake Disasters, and Seismic Design of Diaphragms, Chords and Collectors*. In the early phases of this program, each center was to produce at least one module per year on different aspects of earthquake engineering and hazard-related studies. An inter-center task force of faculty and professional earthquake engineers selects the module topics in consultation with the other two centers. SLC input has been solicited during the beta-testing of each module. Currently many of the modules are being evaluated and distributed for use. Further development in this area is pending evaluation of the existing modules.

3.2.2.2 Instructional Earthquake Simulators

In an effort to increase students' knowledge of earthquake engineering through hands-on experiments, the three EERCs have organized a program for deployment of small earthquake simulators specifically designed for use in a classroom setting. Twenty-three institutions drawn from the three EERCs cooperated in the design of a bench-scale shake table. The initial acquisition was partially supported by an NSF grant and other private funding and has grown to a consortium of over 40 institutions know as ***University Consortium for Instructional Shake Tables*** UCIST. The equipment is used to integrate earthquake engineering into the undergraduate curriculum. Classroom demonstrations and "hands-on" experiments are conducted at all levels in order to have a significant impact on the curriculum. In addition, the shake tables are displayed and demonstrated at public awareness events, including: state fairs, primary and secondary schools, and local community disaster preparedness programs. In Year 6 (and beyond), the SLCs from the three centers will develop plans for two nationwide competitions in earthquake resistant design, one for undergraduates and one for elementary school children. Also in Year 6, these mini-shake tables were used by middle-school students and teachers through PEER's RET program for demonstrations and for carrying out experiments for science fair projects. See the Chapter 1 and Volume III for additional information.

3.2.2.3 *Curriculum Changes from PEER Activities*

PEER is seeking ways to incorporate its research activities into our earthquake engineering curricula. Some classes directly utilize the Graduate Course Modules developed in previous years, while many others are incorporating PEER research results into the lectures and assignments in a less formal way. Two examples of classes that have been significantly and positively impacted by PEER research are described below.

- **Earthquake Resistant Design of Structures (CE 227)** is a major component of the graduate curriculum at UC Berkeley attended by 40-60 graduate students and visiting scholars. The curriculum for his course has changed significantly in the past five years because of activities within PEER. An online course module was developed by PEER covering many aspects of the course, including the PEER PBEE methodology. In addition to containing course-related notes, the module contains a number of Java applets that allow students to rapidly assess the characteristics of ground motions they would expect at a site, and the effects of differing amounts and types of nonlinearity of structural response. In addition to facilitating the underlying complex computations, these applets allow students to do a lot more "what if" type comparisons so that they begin to develop a better intuitive understanding of the effects of ground motions on structures. In this regard, a computer program BISPEC, partially funded by PEER, has been extensively utilized in class. This program simulates the inelastic response of simple structural systems to up to two horizontal components of ground motion. With its rich graphical interface, students conduct a large number of nonlinear dynamic analyses to assess the effects of various factors such as strength, stiffness, viscous damping, shape of hysteretic loops, geometric nonlinearities, and so on, and develop design response spectra considering the methodologies being developed by PEER. The PEER ground motion database is used extensively in completing classroom assignments. Lastly, numerous examples of structural response of more complex systems are presented in the course based on results obtained using the PEER-developed OpenSees computational framework. In completing the final design project for the course, a number of students use OpenSees to carryout their analyses.
- **Case Studies in Seismic Design (Architecture 259X**) is a new course (Spring 2003) in the Department of Architecture at UC Berkeley. It takes advantage of the campus retrofit program and the PEER Center's studies of PBEE. The class has a mix of students from Architecture and Civil Engineering. The class introduces the students to performance design principles and requires that each student undertake a case study of the retrofit design of one of the UC campus buildings. The students are investigating the history of the campus program in terms of campus policy and design precedents. In addition, for each case study, they review the design goals, performance objectives, and methods of retrofitting a major building. Collectively, the student work will be the basis for a guide to the seismic retrofit program on the Berkeley campus, in anticipation of the 100-year

anniversary of the 1906 earthquake.

3.3 Future Plans

Some of the most significant advances that the PEER Education Program has delivered from the center's inception stem from two fundamental themes:

a) Development of an instructional and research environment within PEER that provides a natural growth for a student's interest in all aspects of earthquake engineering through a variety of undergraduate and graduate student opportunities.
b) Cooperative efforts with the MAE and MCEER Education programs.

PEER has promoted a student-friendly environment. The development of a *PEER student culture* has been evident and has encouraged Summer Interns to become Earthquake Engineering Scholars who, in turn, have become active participants in the Student Leadership Council as well as graduate researchers and faculty members. The PEER Center Director has been a staunch supporter of these student programs, and has provided a direct and sincere communication link to the students through the Student Leadership Council and Student Association. Continued support of PEER's student-friendly environment will be one of the primary goals in the future.

The intra-university and inter-university networking opportunities provided for students by PEER are leveraged with the cooperative programs established with MAE and MCEER, creating academic and social relationships across center boundaries. The cooperative efforts of the three EERCs have provided an environment enabling the students to jump-start their professional contacts – among themselves, EERC faculty, and industry representatives – sooner than those students who have not participated in the EERCs.

Accordingly, the PEER Education program intends to continue those programs that have served the students well, including *PEER Summer Intern Programs*, *Earthquake Engineering Scholars Course*, *REU Program* (including *Symposium for Young Researchers*), *Student Leadership Council*, and *Education Forums*. In addition, we will evaluate the effectiveness of our new programs, including the *Tri-Center Doctoral Student Exchange*, the *PEER Lecture Series*, and the *Tri-Center Earthquake Field Study*.

While we have implemented several new programs in the recent past, and are busy supporting those, we still are interested in pursuing additional new programs in the near future such as:

- ***Undergraduate Shake Table Competition:*** We are constantly looking for new ways to use our UCIST Shake Tables. We used them in Year 6 for testing Science Fair Projects through the RET program, and considered developing a K-12 LEGO competition, similar to that held at UC Irvine each year. While considering this competition, the PEER SLC, along with the SLC's from MAE and MCEER, have started to pursue the idea of an undergraduate shake table competition. Conceptually, this will involve teams from several universities building earthquake-resistant structures within specified constraints. The competition would begin within each EERC, and culminate in a Tri-Center Competition. This is in the initial planning stages, and is planned for a trial run in Year 7.

- ***Earthquake Education Series on UCTV:*** PEER has begun work with UCTV on developing a Earthquake Education Series that would combine on-demand video and narrowcasting from the PEER Education Website, together with broadcasting on UCTV via satellite to reach a broader audience. The series would consist of up to six short documentaries on PEER Interns and Graduate Students working on Earthquake

Engineering research, as well as short video clips of PEER faculty explaining key issues and concepts in Earthquake Engineering. It is anticipated that funding for this effort would take the form of a NSF Informal Science Education Supplement. In order to demonstrate the feasibility of the series, a 15-minute pilot is currently being scripted by UCSD-TV. The focus of this pilot will the LEGO Structure Competition at UC Irvine on May 17, 2003.

- ***Curriculum Changes from PEER Activities:*** PEER aims to facilitate the incorporation of research results into our earthquake engineering curriculum. Some current curriculum developments have already been described. The Education Committee will be evaluating ways of accelerating this process.
- ***Increased diversity in student programs*** – PEER has aimed to increase the diversity of students involved in earthquake engineering, but has not succeeded to the degree that it would like. One modification that is planned for Year 6/7 is to modify the approach to selecting students for the Earthquake Engineering Scholars Course (EESC) and other similar programs. For example, in the past, each core campus was able to send up to three participants to the EESC, and the affiliates were represented by only five students. In Year 6, in an effort to reach more diverse group of undergraduates students, only half of the scholars will be coming from the core campuses. The rest will come from current affiliates and potentially from other universities with more diverse student populations.
- ***Increased Undergraduate Involvement in Research:*** One of the criticisms of PEER in Year 5 was the limited involvement of undergraduates in research. We are trying to address this in a number of ways. As a direct solution, PEER is offering supplements to active research awards of approximately $5000 specifically earmarked for undergraduate students, either during the academic year or in the summer. We are increasing undergraduate student involvement in PEER in other ways: adding undergraduate representatives to the SLC, having the PEER Professional Fellows visit undergraduate classes, and by starting the Undergraduate Shake Table Competition.

4. INDUSTRIAL/PRACTITIONER COLLABORATION AND TECHNOLOGY TRANSFER

4.1 Strategic Plan for Industry/Users Collaboration, Outreach, and Technology Transfer

Close collaboration between government, industry, design professionals, and other end-users of PEER products and knowledge are key to the success of the PEER program because they help identify and fill gaps in current knowledge; aid in the development and funding of sector-directed research programs; provide critical review of the strengths, weaknesses, opportunities, and threats relative to the PEER program; and facilitate timely and cost-effective outreach and technology transfer. Therefore, we have endeavored to develop an effective program with appropriate government and industry partners.

Figure 4.1 presents the PEER strategic plan for collaboration and technology transfer to industry, practitioner, and government groups. This plan has developed continuously since its introduction in Year 2. The PEER strategy of collaboration is to seek out and engage key players in government, industry, and business sectors that will be adversely impacted by earthquakes; earthquake professionals who have valuable experience in earthquake mitigation and who will benefit from enhancing their professional expertise; and organizations with existing earthquake outreach and technology transfer programs who can benefit from technology transfer collaborations with PEER. Part of this strategy is to identify the needs and requirements (Figure 2.1) for PEER research, including practical delivery mechanisms that can be utilized by the end users. Another part is to engage practicing professionals with researchers including students, to enhance the research experience and create lasting partnerships between practitioner and researcher. A third essential part of this strategy is to identify and develop relationships that

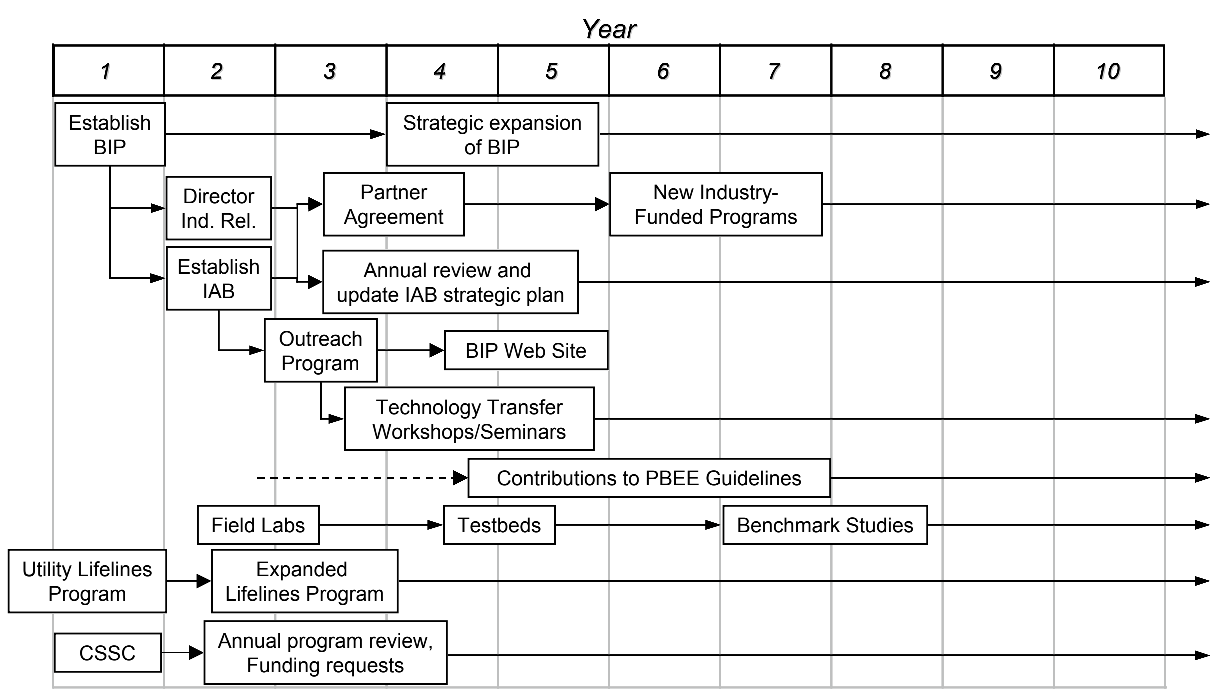


Figure 4.1 - Strategic Plan for Industrial/Practitioner/Government Collaboration and Technology Transfer

result in funding of PEER research and technology transfer programs, with a goal to secure long-term funding to sustain the Center.

With reference to Figure 4.1, the first step in the implementation of our strategic plan was establishment in 1998 of the Business and Industry Partner (BIP) Program as a mechanism for enhancing the relevance of PEER research. When PEER was reorganized under the NSF ERC program in 1999, PEER formed the Implementation Advisory Board (IAB) as a select group of partners to formalize the review of our research and technology transfer activities. The reorganization also sped the already-planned establishment of a new position, the Director of Industrial Relations, to oversee development of the program with the objective of achieving self-sufficiency through sustained government and industry funding. Dr. Andrew Whittaker (now Associate Professor at the State University of New York, Buffalo) previously held that position. Since his departure from the University, we have redefined the position and received permission to recruit for it. However, our initial efforts to recruit this position in 2001-2002 have been unsuccessful. During this period, we have maintained vigilance over this program through a combined effort of the Center Director (Dr. Moehle), the Director of Public Relations and Outreach (Mr. Vaziri), and the Lifelines Program Manager (Dr. Riemer).

Another important development has been establishment in Year 3 of the office for Public Relations and Outreach under the direction of Mr. Parshaw Vaziri. The program supports a range of functions. It fosters communications within PEER, between PEER and the University, and between PEER and the outside community. It serves a public relations function, ensuring that inquiries are answered promptly and that news releases are prepared regularly and distributed widely. It organizes workshops, seminars, and meetings for a wide audience. Finally, it is responsible to create web-accessible information for our BIP members, providing access to research results and students.

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, we have 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 identifying new initiatives that may lead to additional funding. PEER works regularly with the CSSC to update its *California Earthquake Loss Reduction Plan*, thereby ensuring that PEER has a voice in the research and outreach directions of the State. The CSSC prepares written progress reports on PEER to the State legislature, and with those makes funding requests to sustain and grow the PEER program.

On the industry side, we established in 1997 a program known as the Utility Lifelines Program (see Chapter 2 for additional details). The Utility Lifelines Program originally was funded by the Pacific Gas & Electric Company (PG&E). Recognizing the need to expand the scope and funding base of the program, we worked with PG&E managers to propose and secure additional funding from the California Energy Commission (CEC). This was further expanded in Years 2 through 5 to include funding from the California Department of Transportation (Caltrans) and Federal Emergency Management Agency (FEMA). Given the expanded focus of the program, we have renamed it the Lifelines Program. The current funding is programmed until around June 2004. We have already began discussions with the funding agencies on program renewal.

Through discussions with our Implementation Advisory Board, we have initiated efforts to develop funding from other government and industry sectors. Identifying and developing those programs is a primary responsibility of the Director of Industrial Relations.

An important development in Year 4 was the formalization of the Business and Industry Partner Agreements. In the past, the agreement was an informal written agreement between the BIP partner and the PEER Center. In Year 4, PEER worked with the Implementation Advisory Board, the University of California Sponsored Projects Office, and the National Science Foundation to formalize the agreements to meet NSF and University requirements. Generic language for the agreements including rights and privileges of all parties was approved in April 2001. The new agreements formed the basis for membership in the BIP program starting in 2001.

The PEER leadership has aimed to contribute to the continued development of performance-based earthquake engineering guidelines and regulations. As part of our strategic plan, we have maintained close working relations with organizations responsible for such developments, including the Federal Emergency Management Agency (FEMA) and the Applied Technology Council (ATC). In 2001-2003 we collaborated with ATC/FEMA in the development of improved methods for nonlinear analysis of buildings. We also were successful in helping establish the structure of the new FEMA-funded program for Development of Guidelines for Performance-Based Earthquake Engineering (ATC 58). Two members of the PEER leadership team (Director Moehle and Thrust Leader May) have seats on the six-member ATC-58 Project Management Committee, Deputy Director Deierlein is a member of the Structural Products team. Two of our industry partners head up the Nonstructural Products and the Risk Management teams, ensuring an efficient path to implementation of the PEER PBEE methodology.

In prior years the Implementation Advisory Board in its SWOT analyses recommended efforts to improve interactions between BIP members, researchers, and students. A strategic planning committee comprising Vanessa Camelo (Chair, Student Leadership Council), Gregory Deierlein (Deputy Director for Research), Ken Elwood (Berkeley Member of Student Leadership Council), James Malley (Chair, Implementation Advisory Board), Jack Moehle (Center Director), and Gerard Pardoen (Assistant Director for Education in 2001) prepared the plan, including the following elements:

- *Earthquake Engineering Scholars Course* – As described in Chapter 3, PEER has been conducting an Earthquake Engineering Scholars Course for selected undergraduate students. During Year 5 we laid plans to include selected BIP members as presenters or discussion leaders in the course. This new direction has been very positive (see Chapter 3).
- *Methodology Testbeds* – In Year 5 PEER established the PEER Methodology Testbeds under the recommendation of the Scientific Advisory Committee and the Implementation Advisory Board. As described in Chapter 2, the testbeds involve detailed implementations of the PEER PBEE methodology and involve BIP members in intensive studies.
- *PEER Annual Meeting* and *Student Day* – The PEER Annual Meetings have attracted as many as 300 participants including researchers, students, BIP members, and the public. Starting in 2002, we convened a Student Day, which included meetings among students and BIP members, including oral and poster presentations about research and practice.

- *PEER Visiting Professional Program* – During Year 5 we developed and began to implement plans for the PEER Visiting Professional Program. Students and faculty at PEER core universities identify BIP partners whom they would like to invite as part of the program. The students plan the daylong meeting to include student/faculty/industry interactions and a seminar by the industry representative.

4.2 The PEER Business and Industry Partner Program

The PEER Business and Industry Partner (BIP) Program is the formal mechanism for engaging industry partners in the PEER programs. The program was initiated when the PEER Center was first established in 1998. As first established, PEER personnel recruited potential members annually and secured their membership through signatures on a form prepared by PEER. The agreement established a membership fee linked to company size and secured informal agreement of the partners to participate in PEER programs. The program was very successful in engaging the professional community in PEER activities. However, NSF, and subsequently UC Berkeley, deemed the program unsatisfactory because the agreement was not an officially approved contract of the University and because intellectual property rights were not included in the agreement.

Starting in 2001, PEER established a more formal mechanism for the BIP program through a contractual agreement between the Partner and UC Berkeley. A generic agreement is included in the Appendix II. The main aspects of the agreement are:

- Formal statement of the interest of the Partner in joining PEER. The Partner selects a level of participation consistent with the company size and whether they are interested in intellectual property and licensing agreements. A different membership fee is associated with each membership level. Indirect costs are waived on all membership fees.
- A series of Partner benefits is defined. Those members joining at the Sustaining Member level receive the regular benefits plus early access to intellectual property.
- An Implementation Advisory Board is promised; members joining at the Sustaining Level have automatic membership on the Board.

As in the past, the BIP members are informed of PEER activities through regular mailings. They are encouraged to attend all research meetings, and are invited to the PEER Annual Meeting. We also convene at least once per year a BIP reception and dinner to recognize the contributions of the Partners.

Table 4 lists current Member, Affiliate, and Contributing members of the Business and Industry Program. A Member is an organization that has signed the membership agreement (Appendix II); An Affiliate is an organization that provides cash to the program under the PEER strategic plan but which has not signed the membership agreement. A Contributing organization provides other non-project-specific support to the Center. It is noteworthy that the organizations providing the primary funding to the Lifelines Program qualify as Affiliate Members; the contracts were executed prior to formalization of the BIP Program in 2001 and contracting complications prevented signing the formal BIP agreement at this time, even though these partners in all other practical measures are fully engaged in our BIP program.

Table 5 tracks the membership over the life of the BIP program. Note that the formal membership agreement (appendix II) was not executed until 2001. Membership prior to 2001 is based on the less formal partnership agreement.

4.3 Program for Public Relations and Outreach

PEER has established its Office of Public Relations and Outreach to serve several functions. It improves communications within PEER, between PEER and the University, and between PEER and the outside community. It serves a public relations function, ensuring that inquiries are answered promptly and that news releases are prepared regularly and distributed widely. It organizes workshops, seminars, and meetings for a wide audience. Finally, it is responsible to create web-accessible information for our BIP members, providing access to research results and students.

During the past year, the office of Public Relations and Outreach has continued its effort to increase the level of communication between the Center and its participants, as well increasing outreach to the earthquake engineering community. Highlights of outreach activities during the past year have included:

- Logistical management of PEER's research workshops and meetings, including technical, informational, and organizational events
- Changes to the format for the PEER Annual Meeting; the changes were designed to increase participation and interaction among the meeting attendees.
- Continued development and preparation for a major international conference PEER is co-sponsoring in July 2003, the *Ninth International Conference on Applications of Statistics and Probability in Civil Engineering*. Recent activities have included the coordination of over 600 anonymous reviews of manuscripts submitted to the conference.
- The recent hiring of a web and electronic document specialist will allow for further improvements and streamlining of PEER's communication vehicles.
- Transfer of the *PEER Report Series* to Outreach. This series of technical reports was initiated in 1998, and is one of the primary mechanisms for delivering research results to the earthquake engineering community. Table 4.1 shows the number of reports published in each year of the series.

Table 4.1 PEER Report Series

Publication Year	# of Reports Published
1998	8
1999	14
2000	10
2001	16
2002	17

PEER has sponsored or co-sponsored several events related to the progress and products of the PEER program as well as those related more broadly to performance-based earthquake engineering. Table 4.2 provides details of events in the past three years.

Table 4.2 Outreach Activities

Date of Event	Title of Event	Location	Type of Event	Description	Number of Attendees
3/03	PEER Annual Meeting	Palm Springs, CA	Conference and Poster Session	Focused discussion sessions built around themes which crossed over research thrust areas. Poster session for students to explain their projects to members of industry and other meeting attendees.	169
3/03	PEER Workshop Shallow Foundations	Davis, CA	Workshop	To disseminate a summary of research findings from PEER research on shallow foundations and discuss a plan for future related research, and to receive feedback from peers on helpful direction in the ongoing development of procedures	20
10/02	4th US-Japan Workshop on Performance-Based Earthquake Engineering for Reinforced Concrete Building Structures	Toba, Japan	Workshop	This workshop brought together researchers and practitioners to discuss developments in performance-based earthquake engineering.	27
9/02	Lifelines Program Research Results and Implementation Briefing	Berkeley, CA	Seminar	This Briefing focused on the results and implementation of recent applied seismic research conducted by the PEER Lifelines Program. Emphasis was placed on the immediate and near-term benefits that stem from this research, and on means to maximize the value of these results through broad application by a spectrum of utilities and transportation systems.	50
9/02	OpenSees User and Developer Workshop	Berkeley, CA	Workshop	The first portion of the workshop was geared towards users who have little or no experience using OpenSees. The latter days were aimed at OpenSees code writers.	51
8/02	International Conference on Advances and New Challenges in Earthquake Engineering Research (ICANCEER)	Harbin and Hong Kong, China	Conference	The program will focus on new advances in earthquake engineering and innovative solution approaches. Research for development and application of advanced technologies, as well as intelligent infrastructure engineering was covered.	
7/02	Seventh National Conf. On Earthquake Engineering (7NCEE)* **financial co-sponsor*	Boston, MA	Conference and Poster Session	Provides an opportunity for researchers and practitioners to share the latest knowledge and techniques for understanding and mitigating the effects of earthquakes.	750

5/02	UC Berkeley–CUREE Symposium in Honor of Professors Ray Clough and Joseph Penzien	Berkeley, CA	Conference	PEER co-sponsored this conference featuring advances in earthquake engineering in recognition of the notable contributions of the honorees.	193
4/02	Third National Seismic Conference and Workshop on Bridges and Highways	Portland, OR	Conference	PEER co-sponsored this conference featuring current national and regional practices and research on earthquake-resistant bridges.	351
4/02	Large-Scale Unbonded Braced Frame Assemblies Briefing	Berkeley, CA	Workshop	PEER organized this program in collaboration with the UC Berkeley Office of Capital Projects to review a testing program on large-scale unbonded braced frame assemblies.	52
4/02	2002 Cal Day Exhibit	Berkeley, CA	Exhibit/ Display	This exhibit at Cal Day, UC Berkeley's annual open house to prospective students and the public, was aimed at raising awareness about PEER and how to mitigate the danger that earthquakes pose.	-
3/02	Exhibit at California State Capitol	Sacramento, CA	Exhibit/ Display	PEER's exhibit in the Capitol Building was aimed at both members and staff of the California Legislature, but also at visitors to the Capitol. The purpose of the exhibit was to raise awareness about PEER and how to mitigate the danger that earthquakes pose.	-
1/02	PEER Annual Meeting	Oakland, CA	Conference and Poster Session	Research digests presented recent results and progress in the PEER research program. A special session was convened for PEER students to present their research to members of PEER's BIP program. A BIP Banquet honored current members.	240
10/01	Seismic Risk and Communication: WSSPC Annual Conference 2001	Sacramento, CA	Conference	PEER co-sponsored this conference with primary focus on communication of earthquake risk.	300
9/01	Pier Testing Briefing	Richmond, CA	Workshop	PEER organized this program in collaboration with the UC Berkeley Office of Capital Projects to review an upcoming pier test program.	45
8/01	3rd US-Japan Workshop on Performance-Based Earthquake Engineering for Reinforced Concrete Building Structures	Seattle, WA	Workshop	This workshop brought together researchers and practitioners to discuss developments in performance-based earthquake engineering.	36
5/01	2nd National Earthquake Ground-Motion Mapping Workshop	San Francisco, CA	Workshop	PEER co-sponsored this workshop aimed at providing input to USGS on ground motion mapping.	75

4/01	2001 Cal Day Exhibit	Berkeley, CA	Display/ Exhibit	This exhibit at Cal Day, UC Berkeley's annual open house to prospective students and the public, was aimed at raising awareness about PEER and how to mitigate the danger that earthquakes pose.	-
1/01	OpenSees User's Workshop	Richmond, CA	Workshop	PEER organized this meeting to introduce OpenSees to PEER researchers and others.	36
1/01	PEER Annual Meeting	Oakland, CA	Conference and Poster Session	This meeting featured focus papers on PEER's general mission and scope, in plenary, breakout, and poster sessions.	274
12/00	Business and Industry Partners Banquet	Berkeley, CA	Seminar	Technical presentations on current PEER research, a discussion on the BIP program, and a report from the Implementation Advisory Board.	52
11/00	Performance-Based Earthquake Engineering and Risk Management Workshop	Richmond, CA	Workshop	PEER convened this meeting to discuss aspects of risk management as they relate to various financial instruments.	15
10/00	Workshop on Critical Ground Motion Parameters for Structural and Geotechnical Performance Indices	Richmond, CA	Workshop	This workshop was organized to build a consensus among PEER researchers on ground motion Intensity Measures.	40
9/00	2nd US-Japan Workshop on Performance-Based Earthquake Engineering for Reinforced Concrete Building Structures	Sapporo, Japan	Workshop	This workshop brought together researchers and practitioners to discuss developments in performance-based earthquake engineering.	26
8/00	Non-Structural Components Workshop	Irvine, CA	Workshop	This workshop was held to help develop a research plan for the coordinated study of nonstructural components with the PBEE framework.	30
3/00	US-Japan Workshop on the Effects of Near-Field Earthquake Shaking	San Francisco, CA	Workshop	Presentation of results of recent research in the U.S. and Japan related to the effects of near-field earthquake shaking.	155
3/00	Performance Based Engineering Concepts for Bridges	Stanford, CA	Workshop	Workshop organized to development a framework for PBEE of bridges.	28

5. RESOURCES, CONNECTIVITY, MANAGEMENT, AND FINANCES

5.1 Institutional Configuration, Personnel, Equipment, and Space

5.1.1 Institutional Configuration

PEER is instituted as a consortium of Core and Outreach Institutions. The *Lead Institution* is the University of California, Berkeley, where the Center Director and core administration are located. The *Core Institutions* are those universities that initiated founding of the center, collaborated to achieve the matching funds, and are the primary locations for PEER activities. The *Outreach Institutions* include (a) institutions that receive funds from PEER to conduct very focused work with or for the center, (b) organizations whose PIs work primarily at their own institutions in partnership with PEER staff but receive no funds from PEER, and (c) organizations directly involved with PEER educational or outreach activities.

Table 6 (see end of this chapter) lists the Institutions executing PEER's research, technology transfer, and education programs. The growing number of institutions involved with PEER represents a major change from the original PEER structure. Formerly, PEER was envisioned as comprising a Lead Institution, eight Core Institutions, and nine Affiliated Institutions. As the influence and funding base of PEER has grown, a new and expanded vision of the consortium (as reflected in Table 6) has developed.

5.1.2 Personnel

Table 7 (see end of this chapter) provides a count of those members of the PEER team during the Reporting Year that are considered to be PEER Personnel by virtue of managing, leading, and carrying out PEER's research, education, technology transfer, and outreach activities. The vast majority of them carry out the center's mission through involvement in projects that contribute directly to the center by fulfilling its strategic plan. Included in this count are all people who worked on a paid or unpaid basis on center research, technology transfer, and education activities funded by all sources.

5.1.3 Equipment and Space

The PEER headquarters is at the Richmond Field Station of the University of California, Berkeley. All activities are centrally administered at this location. One administrative support office at UC San Diego assists in the day-to-day administration and management of the education activities of the center. Satellite office space on the UC Berkeley campus has been set aside during Year 6; however, that space is not currently available as a result of programmed seismic rehabilitation work.

The PEER headquarters is responsible for overall administration of the center program. NSF and primary matching funds are held entirely by the PEER headquarters until subcontracts are made to individual principal investigators at PEER institutions. The PEER headquarters also serves as a central clearinghouse for all PEER activities, and publishes research reports, newsletters, and Internet information from the central location.

Overall research coordination and specific responsibility for the core research program funds is the responsibility of the Deputy Director for Research (Gregory Deierlein). Administration of all research activity is through personnel at the PEER headquarters at UC Berkeley.

Education program coordination is carried out partly at the UC San Diego office. This office is responsible to convene the Education Committee and develop an education program, develop program announcements and requests for proposals, and make recommendations for education program funding to the Center Director. This office also is responsible for the day-to-day management of the education program.

The center brings outstanding and unique research facilities together in a single network. Experimental facilities include the largest centrifuge, the largest three-dimensional shaking table, the largest tsunami wave tank, and the largest strong-wall/test floor facilities currently operating in the US. Five NEES equipment sites are at PEER core and affiliated universities. The network of unique facilities, linked by a modern telecommunications system, facilitate multi-institutional coordinated research to be carried out as part of the center.

Each of the participating universities features many state-of-the-art networked computer facilities. In addition, the center has direct access to the NSF-established super computer center at UCSD. The center has established an electronic network including video-conferencing capabilities among the participating institutions to facilitate communications and to extend involvement in all facets of the education and research programs.

Information systems for earthquake engineering are available at UC Berkeley and Caltech through the National Information Service for Earthquake Engineering as well as the CUBE/REDI programs for real-time earthquake information, and at USC as part of the SCEC Outreach Program. The center works with and through these and other established information systems to introduce an enhanced vision of earthquake engineering research dissemination.

5.2 Broader Outreach and Connectivity with Other Centers

PEER benefits from broader outreach and connectivity with several other centers, especially but not exclusively in the earthquake field. Primary activities/collaborations include the following:

- *Tri-Center Collaboration with US Earthquake Engineering Research Centers* – The three EERCs maintain a Council of Center Directors to provide linkages among the centers to help identify mutual areas of interest; to avoid conflicts or unproductive duplicative efforts; and to coordinate and promote national and international activities. PEER also has promoted tri-center strategic planning of research and education programs. This effort is described in detail in Volume III of this report.
- *Southern California Earthquake Center* – PEER and SCEC have collaborated since the inception of PEER. Service on each other's Scientific Advisory Committee ensures early awareness and influence on ongoing activities, and the SCEC Implementation Interface promotes and identifies specific and detailed collaborations between the two centers (http://www.scec.org/aboutscec/020812peer.html).
- *Network for Earthquake Engineering Simulation* – PEER leadership and researchers are active leaders in the NEES program, and PEER funds research to support NEES advancements and integration with the PEER program.
- *Mississippi State University, Engineering Research Center* - PEER has collaborated with the MSU-ERC and the Quake Project at Carnegie Mellon University on Seismic

Performance of Urban Regions (SPUR). The project integrates ground motion simulation technology (CMU), structural and geotechnical simulation for performance (PEER), and system integration and visualization (MSU) to create model-based scenarios of the impacts of earthquakes on the built-environment in an urban region.

- *Asian-Pacific Network of Centers in Earthquake Research (ANCER)* – The three US EERCs provided leadership in formation of the Asian-Pacific Network of Centers in Earthquake Research (ANCER) that has attracted member centers from Taiwan, Korea, China, and Japan with many other centers wishing to join at present. Two international earthquake-engineering conferences (Harbin, PRC and Hong Kong, August, 2002) have been held and another is scheduled for 2003.

- *National Center for Research in Earthquake Engineering (NCREE)* **-** PEER has a formal collaboration agreement with NCREE in Taipei. The two centers have collaborative research to utilize data from the 1999 Chi-Chi earthquake, and collaborate on large-scale testing and analyses of reinforced concrete and composite steel-concrete structures.

- *US-JAPAN Programs* - PEER has co-sponsored four annual workshops on PBEE for reinforced concrete buildings, with a fifth workshop planned for September 2003. PEER also has co-funded studies on ground deformations and liquefaction of mutual interest to US and Japanese utility companies and geotechnical researchers.

- *ATC 58 Project to Develop Performance-Based Design Guidelines* – The FEMA-funded ATC 58 project has a long-range plan to develop PBEE guidelines. The project explicitly is organized to take advantage of PEER developments. PEER key participants have key roles in project management and technical develop committees of the ATC 58 project.

- *Memoranda of Understanding* – PEER has entered into memoranda of understanding with several key international organizations, including: European Commission's Joint Research Centre in Ispra, Italy; Disaster Prevention Research Institute (DPRI), University of Kyoto; Earthquake Disaster Mitigation Research Center (EDM), National Research Institute for Earth Science and Disaster Prevention, Japan; and National Center for Research in Earthquake Engineering (NCREE), Taiwan National University.

5.3 Management Systems and University Partnership

The PEER programs are organized and managed to ensure strategic planning and program coordination, project and PEER personnel communications, outreach communications, and effective utilization of program resources. The organizational structure is outlined in the following paragraphs.

5.3.1 Organization Chart, Key Individuals, and Committees and Boards

Figure 5.1 shows an organization chart for PEER. This chart depicts management, leadership, and oversight relations.

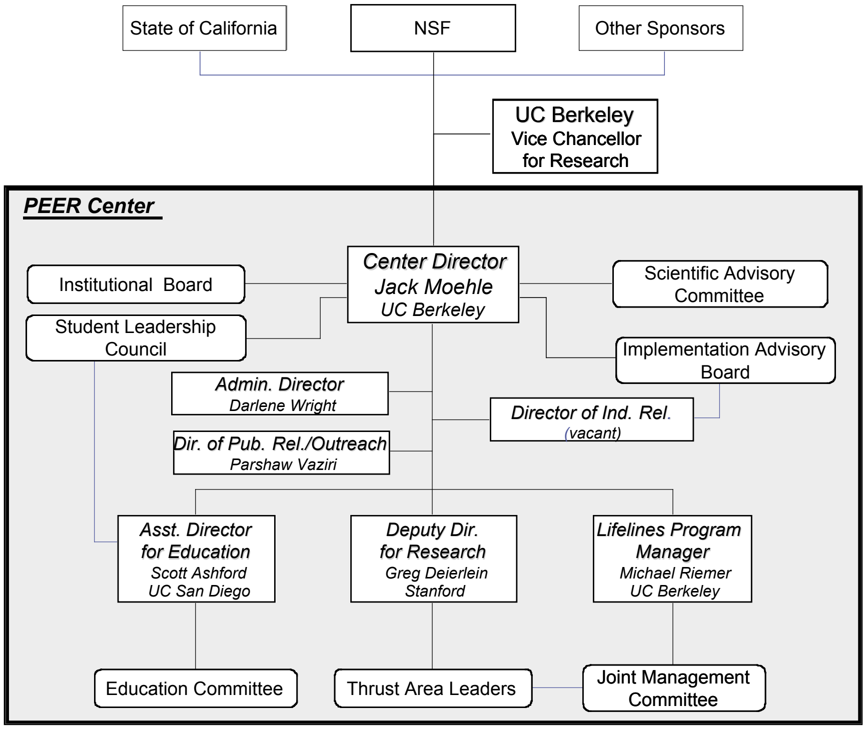


Figure 5.1 - Organization Chart

The ***Center Director***, Professor Jack Moehle (UC Berkeley), is the chief executive officer of the center. He is responsible for administering the center in accordance with the requirements of NSF. He also is responsible for creating an atmosphere of intellectual creativity that stimulates innovation and promotes team coordination. He is responsible for staffing, fiscal, and resource management. The Center Director recommends to the Institutional Board the appointment of key individuals. The Center Director reports to the Vice-Chancellor for Research at UC Berkeley.

The ***Administrative Director***, Ms. Darlene Wright (UC Berkeley), assists the Director in management of PEER; acts as guardian of rules, regulations, and policies; serves as information gatekeeper and resource for center members; and is the financial and personnel manager.

The ***Director of Industrial Relations*** leads efforts to develop the Business and Industry Partner Program, and is the primary contact with the Implementation Advisory Board. Currently, the responsibilities of this position are shared by the Director (lead responsibility), Director of Public Relations/Outreach, and the Program Manager for the Lifelines Program. This position has been approved by the UC Berkeley Vice Chancellors Council but is unfilled at the time of this writing.

The ***Director of Public Relations and Outreach***, Mr. Parshaw Vaziri (UC Berkeley), is responsible for maintaining and developing public relations materials and providing broad visibility for the center and its activities. This position has primary responsibility for events management and regular communications within the center among all participants and sponsors.

The ***Deputy Director for Research***, Professor Greg Deierlein (Stanford University), manages the research program and is responsible to the Center Director for all research activities. The Deputy Director recommends organization of the research program into thrust areas, and recommends Thrust Area Leaders, who are appointed by the Center Director subject to approval of the Institutional Board. The thrust area leaders along with the Deputy Director compose the ***Research Committee,*** which organizes details of the research program. They are responsible for developing strategic plans, convening coordination meetings, monitoring progress, and preparing written summaries of work in the research program. For membership, see Table 5.1.

Table 5.1 –Research Committee

Member
Greg Deierlein, *Chair*
Mary Comerio
Ahmed Elgamal
Gregory Fenves
Helmut Krawinkler
Stephen Mahin
Peter May
Jack Moehle, ex-officio

The ***Lifelines Program Manager***, Adjunct Professor Michael Riemer (UC Berkeley), is responsible in collaboration with the Center Director for developing and managing the Program of Applied Earthquake Engineering Research on Lifeline Systems. Director Moehle chairs a ***Joint Management Committee***, consisting of members from PEER and the program sponsors. The JMC defines the research program, reviews proposals, selects investigators, reviews progress, and evaluates research results. Table 5.2 lists JMC membership.

Table 5.2 - Joint Management Committee for the Lifelines Program

PEER	California Energy Commission
Jack Moehle (Chair)	David Chambers
Michael Riemer	Laurie ten Hope
Caltrans	**Pacific Gas & Electric, Co.**
Abbas Abghari	Norman Abrahamson
Brian Chiou	Lloyd Cluff
Cliff Roblee	Kent Ferre
Tom Shantz	Eric Fujisaki
	Stuart Nishenko

The ***Assistant Director for Education***, Professor Scott Ashford (UC San Diego), organizes and conducts the Education Program through the ***Education Committee***, and is responsible to the Center Director for all education activities. Membership on the Education Committee is determined by the Assistant Director for Education, and includes representatives from each Core Institution and from affiliated institutions. Table 5.3 lists current members. The Assistant Director for Education also is responsible for oversight of the Student Leadership Council (described later).

Table 5.3 - Education Committee

Member	Affiliation
Scott Ashford, *Chair*	UC San Diego
Pedro Arduino	U Washington
James Beck	CalTech
Tara Hutchinson	UC Irvine
Boris Jeremic	UC Davis
Erik Johnson	USC
Abraham Lynn	Cal Poly State U
David McLean	Wash. State U
Kurt McMullin	San Jose State U
Charles Menun	Stanford
Jack Moehle, *Ex Officio*	UC Berkeley
Khalid Mosalam	UC Berkeley
Ian Robertson	U Hawaii
Jonathan Stewart	UC Los Angeles
Solomon Yim	Oregon State U

The ***Institutional Board*** (Table 5.4) represents the participating universities, with one appointed member from each of the Core Institutions and one appointed member to represent all affiliated institutions. The Institutional Board establishes policy and reviews and approves financial and administrative activities as well as all appointments of key individuals for the center. The Institutional Board will recommend to NSF and the host institution any changes in the Center Director if this becomes necessary, and will consider adding or removing member institutions. The Center Director and the Deputy Director for Research are ex-officio members of the Board.

Table 5.4 - Institutional Board

Member	Affiliation
Paul Jennings, *chair*	CalTech
Thalia Anagnos[1]	San Jose State U
Medhat Haroun	UC Irvine
I.M. Idriss	UC Davis
Anne Kiremidjian	Stanford
Steve Mahin	UC Berkeley
Charles Roeder	U Washington
Joel Conte	UC San Diego
John Wallace	UC Los Angeles
L. Carter Wellford	USC

[1] Affiliated Institutions Representative

A ***Scientific Advisory Committee*** provides external review of the PEER programs. It advises on center goals, planning, research thrusts, and products relative to regional and national earthquake risk mitigation needs. The membership includes academic, research organization, and advanced applications industry sectors. Current membership of this committee is identified in Table 5.5.

Table 5.5 – Scientific Advisory Committee

Member	Affiliation
Don Anderson	CH2M Hill
Jacobo Bielak	Carnegie Mellon University
Roger Borcherdt	US Geological Survey
Raymond Burby	U North Carolina at Chapel Hill
Ron Hamburger, *Chair*	Simpson Gumpertz & Heger
Tom Jordan	SCEC
James Jirsa	University of Texas at Austin
Ron Mayes	Simpson Gumpertz & Heger

The ***Implementation Advisory Board*** consists of selected members of the Business and Industry Partner Program. The IAB reviews PEER's research programs and products, and recommends ways to improve utilization of results in the private and public sectors. Table 5.6 lists current members.

Table 5.6 – Implementation Advisory Board

Member	Affiliation
James Malley, *Chair*	Degenkolb Engineers
Fadel Alameddine	California Dept. of Transportation
Robert Bachman	Private sector
David Chambers	California Energy Commission
Lloyd Cluff	Pacific Gas & Electric, Co.
John Hooper	Skilling, Ward, Magnusson, Barkshire
Karl Kirker	Washington Dept. of Transportation
Maury Power	Geomatrix Consultants, Inc.
Clifford Roblee	California Dept. of Transportation

The ***Student Leadership Council*** (Table 5.7) organizes student activities and recommends programs to improve student experiences. The SLC is organized and operates according to bylaws it has established, with general oversight from the Assistant Director for Education. The SLC reports jointly to the Center Director and the Assistant Director for Education.

5.3.2 *Strategic Planning, Decision Making, Financial Control, and Communications*

Strategic research planning in PEER is carried out under the leadership of the Center Director and involves the individuals identified in Figure 5.1. Regular teleconference meetings of an Executive Committee (comprising the Center Director, Administrative Director, Deputy Director for Research, Lifelines Program Manager, Assistant Director for Education, and Director of Public Relations/Outreach) ensures that all aspects of the center programs are taken into consideration in strategic and event planning. Various tri-center coordinating committees promote coordination among the three EERCs (see Volume III).

Table 5.7 –Student Leadership Council

Member	Affiliation
Jack Baker	Stanford
Casey Bradford	CalTech
Vanessa Camelo	CalTech
Lijuan (Dawn) Cheng	UC San Diego
Michael Gebman	UC San Diego
George Gimas	U Washington
Emily Guglielmo	UC Los Angeles
Chad Harden	UC Irvine
On Lei (Annie) Kwok	UC Los Angeles
Leonardo Massone	UC Los Angeles
Alberto Salamanca	UC Los Angeles
Raymond Trinh	UC Davis
Patxi Uriz, *Chair*	UC Berkeley

In the core research program, the Thrust Area Leaders are charged with developing thrust area strategic plans, which are then discussed, modified, and coordinated by the Research Committee. In the education program, the Assistant Director for Education is charged with developing an education strategic plan, which is evaluated, modified, and coordinated in discussions within the Executive Committee. Strategic planning is a continual process.

Research project selection is driven by the strategic plan. While primary emphasis is on selecting the most qualified researchers for a task, consideration also is given to building a team of participating faculty and students who are committed to the goals of PEER. PEER also endeavors to fund promising young faculty and faculty from underrepresented groups. Based on the strategic plan, the Deputy Director for Research, with full participation from the Thrust Area Leaders, develops a series of task statements for the next period. If the Research Committee can identify an individual or team specially suited for the task, the task will be directed by mutual agreement to that individual or team. In other cases, a Request for Statements of Interest is distributed and decisions are reached on the basis of responses and negotiations. The Center Director has authority to make final funding decisions.

The Center Director in consultation with the Executive Committee makes strategic and ad-hoc financial decisions. Distribution of funds among programs generally adheres to a strategic allocation plan, which targets percentages of the total budget for specific program areas and attempts to maintain balance in funding among disciplinary areas and among senior and junior faculty. Funding distributions also consider the need to increase participation of individuals from underrepresented groups.

The University of California has an established financial management system that complies with federal, state, and institutional regulations that also govern the PEER Center. Policies and established procedures govern procurement of all goods and services. Knowledge of and adherence to these governmental and institutional regulations is the responsibility of the Administrative Director. Key PEER administrative staff members are aware of cost principles governing expenditures of federal funds (OMB Circular A-21) and procurement procedures prescribed by federal regulations (OMB Circular A-110), and the Cost Accounting Standards.

All pre-award activity is channeled through a centralized Sponsored Projects Office, delegated to be the Authorized Institutional Representative for all agreements (grants, contracts, subawards) with the institution. They also make certain that budgets (rates, benefits, overhead and other allowable costs) and terms and agreements are in compliance with institutional as well as governmental regulations. A centralized Extramural Funding Accounting Office is responsible for the university's invoicing of the awarding agency (if applicable). The invoice is usually presented with a financial progress report required by the agency at the time of invoice.

In previous years, data contained in the Annual Report financial tables reported funds that were committed or obligated to specific research or education projects during that current year as being 'spent.' This resulted in a large discrepancy between UC Berkeley's quarterly Financial Cash Transaction Reports (FCTRs) actuals and the resultant balance amount, or residuals. PEER's Year 6 award was withheld while NSF and UC Berkeley reconciled the apparent differences. Since then, PEER has reorganized its financial reporting structure to meet NSF requirements and begun the enormous task of going back to Year 1 to reconcile all financial activity for each award year through the present. This reconciliation effort is projected to be complete by the end of May 2003.

The multi-institutional nature of PEER requires special efforts to foster communications and collaborations. These communications begin with regular (usually twice monthly) meetings of the Executive Committee, usually through telephonic means. The Director and Deputy Director communicate more frequently by email, telephone, or face-to-face meeting. The researchers are brought together quarterly to discuss research strategic plans, research needs, and research accomplishments, and quarterly reports are required for each project. All project PIs or their research students, or both, are required to attend these meetings. Information on PEER programs is documented on the PEER web site, in the quarterly PEER newsletter, and by regular email communications. Video-conferencing units have been installed at six campuses.

5.4 Financial Support and Budget Allocations

Summary information on PEER's financial budget, sources of support, actual annual expenditures, and modes of cash from industry are provided in Tables 8-11.

Annual financial support provided to PEER has been at a fairly consistent level for the first six years. During Years 3 through 5, three large contracts were awarded under PEER's Lifelines Research Program; two being awarded from separate areas within the State of California, and one from private industry. The funds received under these contracts were intended to support directed research projects beginning in Year 3 and extending for 3-4 years. Relatively large residuals resulting from the deposit of those funds in a single year are because those funds are expected to be expended over multiple years. Additional residuals arise because of delays between times of obligations and times that expenditures are made and recorded at UC Berkeley. Starting August 2002, with full knowledge of NSF and UC Berkeley, PEER began the punctilious process of reconciling all prior awards, obligations, and expenditures for prior years so that residuals are recovered and applied to current and future years. We have completed this process for all NSF funds and are working on matching and leverage funding at this time.

Since Year 1 PEER has planned to develop an excellent relation with outside sponsors with intent to develop funding programs that extend beyond Year 10. The PEER Lifelines Program (Phase 1), initiated in Year 1 with $2.4M leverage funding from PG&E Company, was further leveraged with PG&E, California Energy Commission, and subsequently California Department of Transportation to provide a stable funding base for lifelines research in Phases 2 and 3. We are working with those sponsors at this time to continue funding into Phase 4. Beginning Year 5, we have worked with the California Seismic Safety Commission to maintain PEER's matching fund base from the State of California and seek other resources for program funding. We have managed to retain most State matching funds despite severe State of California budget shortfalls and ensuing cuts this past year. We will continue to work through these organizations and others to secure stable funding to carry PEER beyond Year 10.

5.4.1 Provision of Cost-Share

The table below shows all required dollar-for dollar cost-share/matching funds information for the current and all prior years. The certified version of this table is located in Appendix II, (4). The two tables differ in dollar amounts because cost share provided by institutions other than UC Berkeley are not certified by UC Berkeley and therefore are not included in the table in Appendix II.

Dollar-for-Dollar Required Cost-share amounts	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Cumulative**
Unrestricted							
State	$1,500,000	$1,500,000	$1,500,000	$1,500,000	$1,500,000	$1,450,906	**$8,950,906**
U.S. University	$270,000	$270,000	$270,000	$270,000	$270,000	$270,000	**$1,620,000**
Unrestricted-total:	**$1,770,000**	**$1,770,000**	**$1,770,000**	**$1,770,000**	**$1,770,000**	**$1,720,906**	**$10,570,906**
Restricted							
U.S. University							
UC Berkeley (lead)	$434,084	$325,451	$202,315	$164,150	$368,763	$372,750	**$1,867,513**
U Washington (core)	$66,668	$181,000	$166,000	$19,000	$0	$0	**$432,668**
UC Irvine (core)	$19,450	$24,303	$0	$0	$0	$0	**$43,753**
UC San Diego (core)	$56,475	$52,324	$0	$0	$0	$0	**$108,799**
Restricted - Total:	$576,677	$583,078	$368,315	$183,150	$368,763	$372,750	**$2,452,733**
TOTAL:	**$2,346,677**	**$2,353,078**	**$2,138,315**	**$1,953,150**	**$2,138,763**	**$2,093,656**	**$13,023,639**

5.5 Proposed Following-Year Budget Request

The NSF budget proposal sheets for Year 7 are provided immediately following Table 11.