2. STRATEGIC RESEARCH PLAN

This section describes the PEER strategic research plan and provides summary information on its research program. The presentation includes information on research outreach as well as 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 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 primary mechanism for developing performance-based earthquake engineering within PEER is the research program, which is guided by a strategic research plan. 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. These are described below.

2.1.1 Systems-Level Research Plan

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.

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

As discussed in Chapter 1, three levels of decisions are served by enhanced technologies for performance-based earthquake engineering. 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

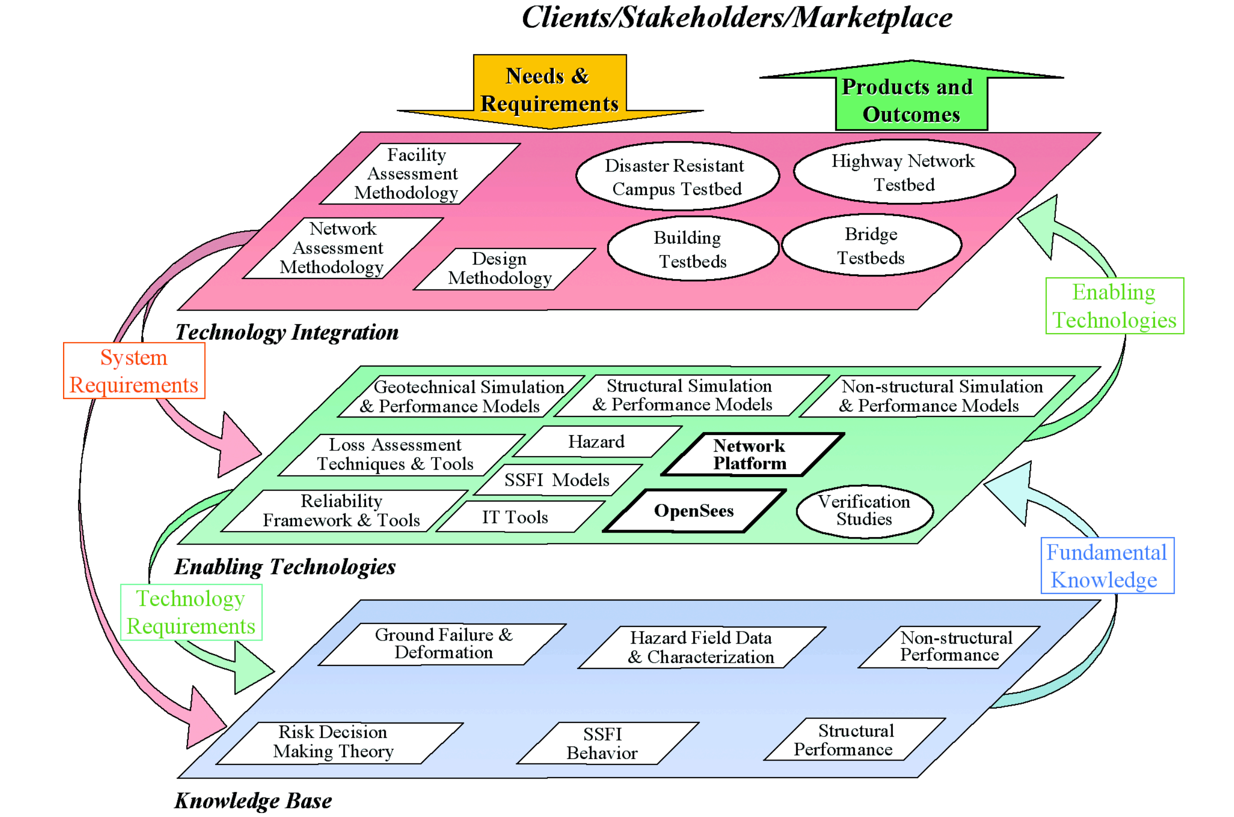

Figure 2.1 - Systems Level Strategic Plan

inform decisions 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 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.

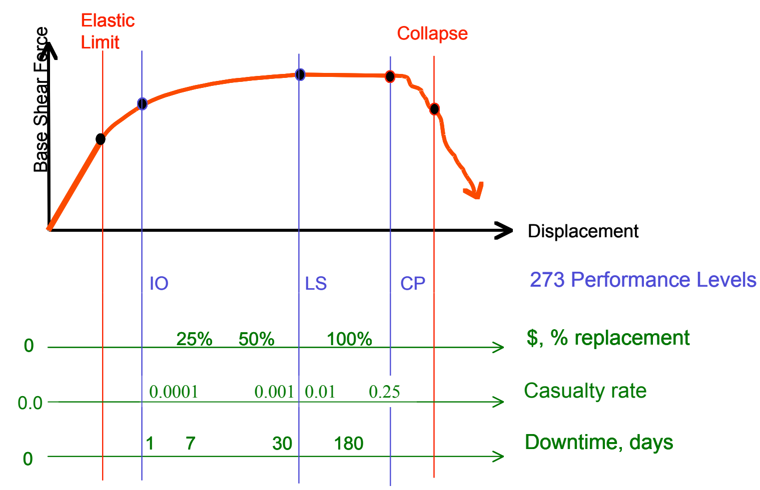

Figure 2.2 – Idealized relation between performance and load-deformation response (after Holmes, PEER 2001 Annual Meeting)

The PEER vision is to advance the state-of-the-art and the state-of-the-practice of performance-based earthquake engineering by numerically tying performance to the losses of interest. As identified in the invited lecture by PEER Business and Industry Partner William Holmes of Rutherford & Chekene at the 2001 PEER Annual Meeting (see http://peer.berkeley.edu), the losses of interest are direct dollar loss, casualty loss, and loss of function (see Figure 2.2). Notably, these are applicable to individual facility design/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 performance-based earthquake engineering.

Holmes further commented on the need for an accepted "performance engine" or "means of verification" to fulfill the promise of performance-based earthquake engineering. In our view, performance-based earthquake engineering 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 (or 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 greater detail in the following sections.

2.1.1.1 Technology Integration Plane

The Technology Integration Plane of Figure 2.1 represents the systems-level applications and studies in performance-based earthquake engineering. 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.

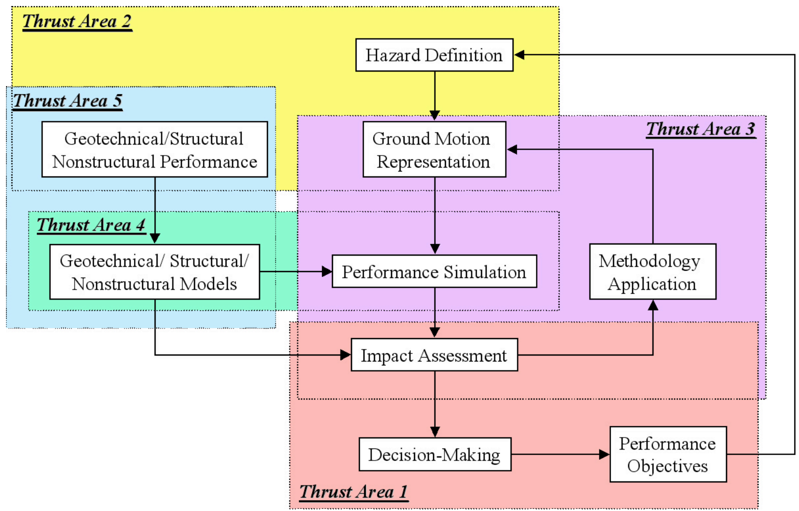

Figure 2.3 – Research elements in the performance-based earthquake engineering methodology and the relation to Thrust Areas.

2.1.1.2(a) 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):

- *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 at this time. As PEER moves forward in Years 6 through 10 it will shift focus to include design. As that occurs, the *Methodology Application* will move to the outer loop to encompass the entire process.

2.1.1.2(b) 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. The following equation has emerged as a promising framework that describes performance in terms of a ***Decision Variable (DV)*** that is related to a probabilistic description of the input ground motion ***Intensity Measure (IM), Engineering Demand Parameter (EDP),*** and ***Damage Measure (DM)***:

$$v(DV) = \iiint G\langle DV \mid DM \rangle \, | \, dG\langle DM \mid EDP \rangle \, | \, dG\langle EDP \mid IM \rangle \, | \, d\lambda(IM) \qquad (1)$$

This equation follows the total probability theorem, where *v (DV)* describes the mean annual probability that *DV* exceeds a specified value, taking into account the variabilities in *DM*, *EDP*, and *IM*. As adopted in the PEER program, the term *DV* generally relates to one of three quantities, specifically mean annual probabilities of dollar loss, duration of service interruption, and casualties.

The expression *G(DV|DM)* is the conditional probability that *DV* exceeds a specified limit for a particular value of *DM*. The expression *G(DV|DM)* can be considered as a fragility function for *DV* as a function of *DM*.

The term *DM* generally describes the damage and consequences of damage to a facility that can then be related to the *DV*. The *DMs* can include, e.g., descriptions of necessary repairs to structural or non-structural elements, quantification of falling hazards, etc. The term *dG(DM|EDP)* is the derivative (with respect to *DM*) of the conditional probability *G(DM|EDP),* i.e., the probability that *DM* exceeds a certain value for a given *EDP*.

Engineering Demand Parameters (*EDP*) include such measures as interstory drift ratio, plastic hinge rotation, floor acceleration, etc., that relate to damage measures (*DM*). The term *dG(EDP|IM)* is the derivative (with respect to *EDP*) of the conditional probability *G(EDP|IM),* i.e., the probability that the *EDP* exceeds a certain value for a given *IM*. Relationships between *EDP* and *IM* are typically obtained through inelastic simulations, which are the essence of PEER's research on developing and implementing structural, geotechnical, SSFI (soil-structure-foundation-interaction), and non-structural damage simulation models.

The final term in Equation (1), $d\lambda(IM)$ is the derivative of a seismic hazard curve, $\lambda(IM)$, which for standard earthquake intensity measures (such as peak ground acceleration or spectral acceleration) can be obtained through conventional probabilistic seismic hazard analysis. An important subject of PEER research is determining seismic intensity measures that best correlate with earthquake-induced damage. The ideal measure may be a vector of multiple intensity measures, such as multiple representations of spectral acceleration, spectral shape, and duration.

Equation (1) serves as 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.

2.1.1.2(c) Proof-of-Concept Testbeds. A series of proof-of-concept testbeds has been established, as identified within ovals in the Technology Integration Plane of Figure 2.1. The purposes of these testbeds are: To focus the research; to test research products and to identify needed research; and to provide a mechanism for PEER researchers and Business and Industry Partners to work jointly on research.

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:

Van Nuys Building – This older concrete building (Figure 2.4) 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.

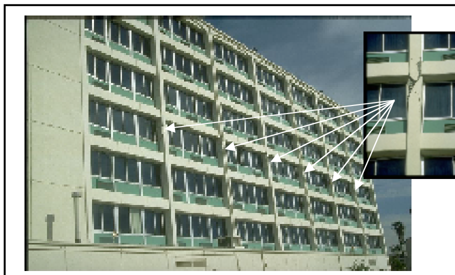

Figure 2.4 – Van Nuys building

Life Sciences Addition Building – This relatively new building has nonstructural systems and valuable lab equipment and experiments that dominate performance decisions. It is a critical research facility on the UCB 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.

Figure 2.5 – Examples of equipment in Life Sciences Building

Humboldt Bay Bridge – Caltrans has found this older bridge to be vulnerable and to require retrofit. 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.

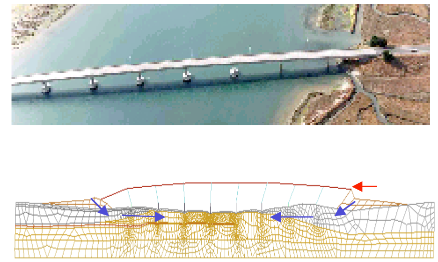

Figure 2.6 – Humboldt Bay Bridge

I-880 Interchange Bridge – A modern reinforced concrete bridge viaduct, this testbed is part of the I-880 highway constructed in the mid-1990's 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 2.7 – I-880 Bridge

Disaster-Resistant Campus –The UC Berkeley campus is located directly adjacent to the Hayward fault, 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.

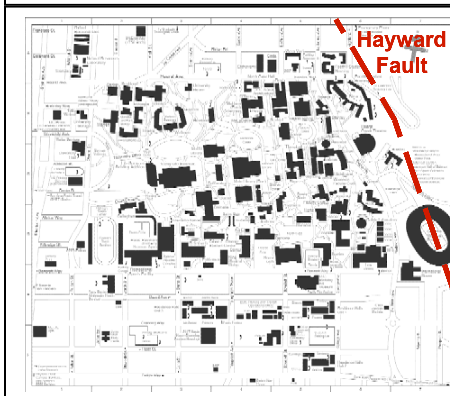

Figure 2.8 – UC Berkeley Campus

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.

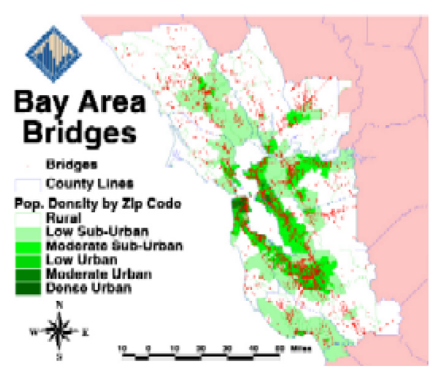

Figure 2.9 – Highway Network

2.1.1.1 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 facilities. Performance-based engineering methodologies are fundamentally based on improved understanding of the behavior of constructed facilities during earthquakes and on representing the behavior with validated simulations. The current state of software for simulating nonlinear behavior of soils and structures is inadequate with incomplete or outdated models, with problematic solution methods, and with an inflexible software architecture that inhibits innovative use of modern information technology and high-performance computing.

  OpenSees addresses these shortcomings. The software is designed to integrate the 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. Also, parallel and distributed equation solvers developed by computer scientists and mathematicians are integrated into the framework for simulation of very large models.

  Looking towards the future, the OpenSees approach will allow combining computational simulation with physical testing. In effect, a component being tested on a shaking table or reaction wall facility is a physical element in a simulation model subjected to simulated boundary conditions. Because these types of interfaces are supported by OpenSees the framework can serve as a basis for hybrid control of physical experiments. This is an area of particular interest for PEER as it envisions its role in the NSF George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program.

  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 make contributions to. A website at *opensees.berkeley.edu* provides not only a download center, but also supports a revision control system, method for submitting contributions, and a bulletin board for communication. This is the first instance of an open-source, community code in earthquake engineering. Currently, more than 200 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. We have introduced testbeds on the Enabling Technologies plane as a means of validating and calibrating OpenSees. These include:

- o *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.
- o *System Simulations* – Recorded earthquake response data for the Van Nuys testbed building and Humboldt Bay Bridge provide 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.
- o *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* – The Network Platform is a suite of analysis and GIS database software 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 final outcomes are an understanding of the highway system performance (important for post-earthquake response and recovery) and an estimate of the expected loss that includes both direct and indirect costs.

  The Network Platform represents earthquake hazards expressed in terms of ground motion, liquefaction, landslides and fault displacements. Thus, it provides a mechanism to incorporate information developed in the PEER Lifelines and Core (Thrust Area 2) research programs. This includes, for example, improved models for predicting ground deformations and bridge damage as a function of vector-based earthquake intensity measures. In the current implementation, the link between hazards (ground shaking and ground deformation) and bridge performance (damage and traffic capacity) is expressed through fragility functions. As computation power and information technologies improve, we envision the capacity to link bridge-specific evaluations made with OpenSees to the Network Platform, thereby improving the resolution beyond that of the generic fragility functions.

  Caltrans has a strong interest in this simulation tool for both pre-planning and rapid emergency response to earthquake damage. Opportunities to expand the Network Program by extending its geographic boundaries and considering ground deformation damage to roadways are under discussion with Caltrans.

- *Other Enabling Technologies* – Several other enabling technologies appear in Figure 2.1. These 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 parallel 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 involve the development and use of visualization tools to improve ways of expressing performance and networks and databases for computation and sharing information.

2.1.1.1 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.

2.1.1.1 Products and Outcomes

The Needs and Requirements described in Section 2.1.1.1 define in a broad sense the products and outcomes of the PEER research program. More specifically, PEER in consultation with its *Implementation Advisory Board* and *Scientific Advisory Committee* has defined a series of products and outcomes. Highlights of these are described below with reference to the three-level strategic planning chart (Figure 2.1); further background and details are presented in the thrust area summaries of Section 2.2.

(A) From the Knowledge Base Plane

- *Hazard Field Data and Characterization* – Data on ground motions, associated mechanisms, and site characterization, including improved site categorizations, organized within accessible databases.
- *Ground Failure and Deformation* – Data on liquefaction and lateral spreading; performance of improved soils; site amplification under a range of conditions, organized within accessible databases.
- *Structural Performance* – Data on performance of nonductile concrete building construction and more modern concrete bridge structural components, organized within accessible databases, integrated with OpenSees, as well as development of concepts for new structural systems of enhanced performance.
- *Soil-Structure-Foundation Behavior* – Data from tests and simulations on interaction between shallow and deep foundations and the soil under a range of site and shaking conditions.
- *Nonstructural Performance* – Data on performance of broad categories of nonstructural components, including contents, mechanical equipment and systems, and connected nonstructural components such as suspended elements and partitions.
- *Risk Decision-making Theory* – Theory on evaluating data and models to produce optimal measures and procedures.

(B) From the Enabling Technologies Plane

- *Hazard* – An online database of ground motion records searchable by relevant parameters, procedures for defining damaging parameters of ground motions, attenuation relations for damaging parameters, and a design module for selecting recorded or synthetic ground motions appropriate for site conditions and performance objectives.
- *Geotechnical Simulation and Performance Models* – Models for the response of soils to ground motion, with emphasis on site amplification models and liquefaction onset and spreading models.
- *Structural Simulation and Performance Models* – Response and performance models for bridge, building, and utility lifeline structural components, including load-deformation models, models for loss of gravity-load capacity, and models to relate mechanical response to performance measures. Models to be validated by tests and include information on uncertainty and application in the methodology.
- *Nonstructural Simulation and Performance Models* – Performance models for architectural, mechanical, and building contents to related input demand parameters with damage and performance measures.
- *Soil-Structure-Foundation Interaction Models* – Response models for bridge and building foundations, including shallow and deep foundations under a range of existing conditions, with applications examples to guide engineers in modeling and selecting appropriate foundations to achieve targeted performance.
- *OpenSees* – A performance simulation software platform capable of large-deformation, inelastic static/dynamic performance assessment of complete soil-foundation-structure-nonstructure systems for bridges, buildings, and other facilities; including a library of test-validated numerical models; and including a program to maintain and disseminate the software.
- *Network Platform* – Software and database modules for simulating seismic hazard, distribution of ground motions, fragility of selected lifelines components, impact on

network functionality, and resulting direct and indirect losses. The modules are capable of being exported for use in related software applications.

(C) From the Technology Integration Plane

- *Facility Assessment/Design Methodology* – By example of the bridge and building testbeds: procedures to assess performance in terms of casualty, dollar, and functional losses; assessment of performance associated with different design levels for generic examples of facility designs; procedures for implementing retrofit designs to deficient facilities; procedures for evaluation of nonstructural systems and components; assessment of the impacts of nonstructural and functional losses on performance of specialized facilities; evaluation of the costs and benefits of nonstructural mitigation; completion of the assessment methodology research, coupled with the worked testbed examples and supported by the broad research within PEER, leading to a final report of recommendations that would supplement FEMA 273/356 on how performance-based earthquake engineering would be implemented within a framework of current accepted approaches.
- *Campus Assessment/Design Methodology* – By example of the UC Berkeley campus testbed: a documentation of the potential losses for a campus of distributed facilities; a method for quantifying the change in potential losses based on enumerated performance standards; a priority system for implementing performance standards.
- *Highway Network Assessment Methodology* – By example of the Bay Area Highway testbed: an assessment of the effectiveness of the Caltrans bridge retrofit program; an evaluation of the interdependence of bridge performance on the network performance, insight on the degree to which highway system analysis should be used to decide performance criteria of individual bridges, either in a generic manner or a network-specific manner; demonstration of the direct and indirect losses related to lifelines networks; understanding of the processes and information bases used by decision-makers, and thereby better understanding of the types of information that research usefully can produce to inform decisions.

One of the broad products of PEER, and the first identified on a list prepared by an ad hoc subcommittee of the IAB and SAC, was a new cadre of students trained through participation in research and in courses to be able to implement new concepts being developed by PEER, including methodology applications and working familiarity with problems spanning the traditional boundaries of seismology, geotechnical engineering, structural engineering, architecture, social sciences, and information technologies. Through their strategic involvement in the testbed studies, participating members in the Business and Industry Partnership also will be trained in the new methodologies.

2.1.1 Major Milestones

Strategic research planning at the Thrust Area level involves identification and coordination of major milestones for each of the Thrust Areas. Figure 2.10 depicts the major milestones, organized by Thrust Area. Section 2.2 provides detailed descriptions of each of the Thrust Area major milestones and the organization of research projects to reach those milestones.

As of the time of this writing, the following have been accomplished.

- *Meaningful Performance Metrics* – The relevant considerations for characterizing performance have been documented as part of studies of decision-making, a PEER synthesis report on decision-making, and in test-beds. The next step to be continued as part

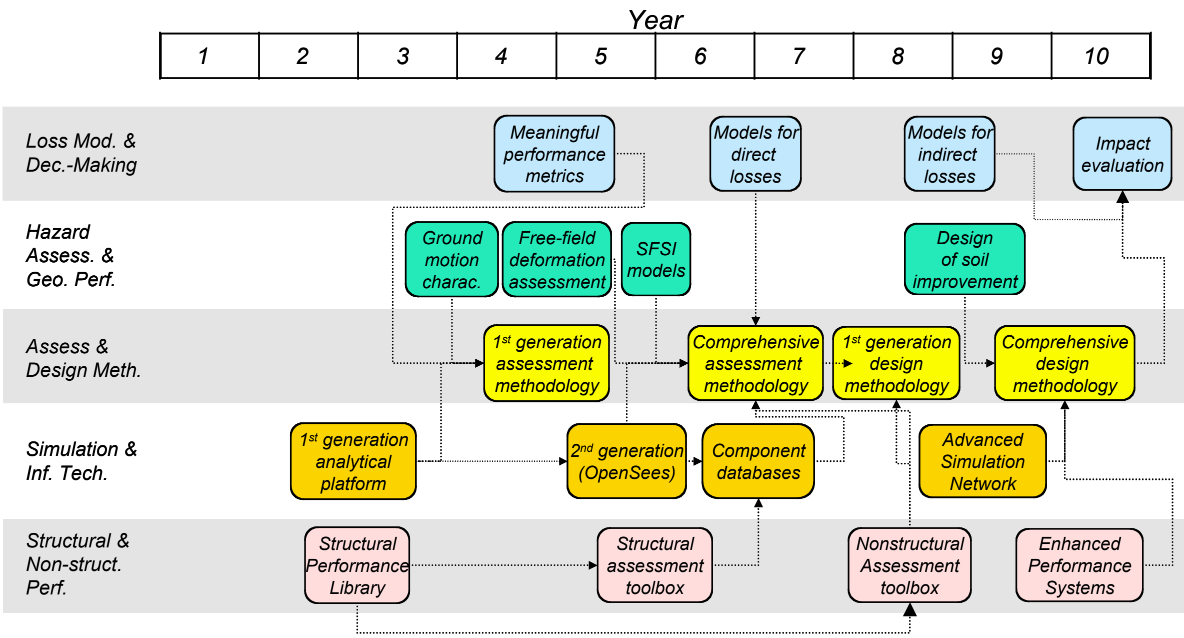

Figure 2.10 - Thrust Area Major Milestones

of Year 6 testbed activities is to quantify performance measures with respect to appropriate metrics and ways of conveying probabilistic aspects and uncertainty. Substantial progress also is being made toward several other milestones.

- *Ground Motion Characterization* – We have made significant progress in defining site characteristics and in identifying the ground motion characteristics of interest, and are proposing new research to facilitate development of ground motions for performance assessment. The ground motion database (http://peer.berkeley.edu/smcat/) has been completed (new motions are added continually) and is used in PEER research and in practice.
- *Free-field Deformation Assessment* – Research in this area has progressed more rapidly than originally anticipated because of the influx of leveraged funding from the Lifelines Research Program. Some research will continue in the future.
- *SFSI Models* – Models for the pile-soil interface (nonlinear p-y and t-z springs) have been developed, calibrated, and implemented in OpenSees. These models are now being exercised in the bridge testbeds. Work is ongoing to develop models and performance limits on shallow foundations.
- *1st Generation Assessment Methodology* – We have identified the framework of this methodology, as reflected in Figure 2.3 and Equation 1, and will fully define the methodology in a brief summary, which will be completed by the end of Year 5. Projects begun in Year 5 and beyond will exercise this methodology in testbeds.
- *1st Generation Analytical Platform* – This Year 2 milestone was completed with the development of Version 1.0 of OpenSees and introduction into the PEER research program.
- *2nd Generation Analytical Platform* – Since the introduction of OpenSees, development has continued at a rapid pace in improving the models for structural and geotechnical components, in improved computational performance, in development of robust solution

strategies for degrading systems, by integrating reliability computation into the platform, and by integration with databases for performance evaluation. The current version 1.2 is considered the second generation of the platform and is being used in the testbed projects. The experience with OpenSees in the testbed projects will be continually fed back to the development team, resulting in Version 2 at the end of Year 6 with new features incorporated as a result of the testbeds.

- *Structural Performance Library* – Initial development of this library was completed in Year 2, with the completion of a set of RC column/pier tests and development of a database of column response parameters. We are continuing to develop and populate the performance library with new data on RC members and connections. During Year 5, we initiated concerted efforts to collect the data in an archived on-line database system that we anticipate can support development of NEES integrated databases.
- *Structural Assessment Tools* – Models to simulate structural response and relate Engineering Demand Parameters to structural Damage Measures have been synthesized during Year 5 and are being applied in the testbed studies. Work is continuing to formalize these into standard fragility curve formats to convey probabilistic data on the relationships.

Substantial progress also is being made toward the other future milestones.

2.1 Thrust Area Research Management and Strategic Plans

This section begins with an overview of the organization and management structure for PEER's five main thrust areas, linkages with industry sponsors through the lifelines program, and other external collaborations. Then, details of the research for each thrust area are described. The thrust area summaries include parenthetical references to individual research projects listed in Table 2, e.g., (#) where the # refers to the first few digits of the project number. Further details of all Year 5 projects are given in the project summaries of Part II of the annual report.

Table 2: Research Program Organization Effort

Page-Completion-Status: Normal Page-Completion-Status: Normal

Table 2: Research Program Organization and Effort - Draft Report
ERC Center: Pacific Earthquake Engineering Research Center

Cluster/Thrust	1: Loss Modeling and Decision-Making		**Cluster/Thrust Leader**		Peter May and Mary Comerio	
Personnel: 13 Faculty Members, 0 Undergraduates, 8 Graduate Students, 0 Post Docs, 2 Other Personnel						
Project	**Leader**	**Investigators (name, department, university)**	**Disciplines Involved**	**Number of Students and Post Docs**	**Current-Year Budget**	**Proposed Year 6 Activity?**
Core Projects						
1152001 - Adoption and Implementation Considerations for PBEE	Peter May	Peter May Political Science University of Washington	Public Policy, Structural Engineering	U=0 G=1 P=0	$35,000	
1162001 - Assessing the Benefits and Costs of PBEE	Richard Zerbe	Richard Zerbe Economics University of Washington Stephanie Chang Geography University of Washington	Economics, Geography	U=0 G=1 P=0	$70,000	
1172001 - Organizational Decision Processes for EQ Mitigation	Jacqueline Meszaros	Jacqueline Meszaros Management University of Washington Ufuk Ince Finance University of Washington	Management, Finance	U=0 G=0 P=0	$70,000	
1182001 - Building Loss Assessment	Eduardo Miranda	Eduardo Miranda Civil & Environmental Engineering Stanford University	Structural Engineering	U=0 G=2 P=0	$70,000	**Yes**
1192001 - Building Loss Assessment	Mary Comerio	Mary Comerio Architecture University of California, Berkeley	Architecture	U=0 G=1 P=0	$50,000	
1202001 - Nonstructural Hazard Mitigation in Life	Mary Comerio	Mary Comerio Architecture	Architecture	U=0 G=1	$50,000	**Yes**

	Sciences Building Testbed		University of California, Berkeley		P=0		
	1212001 - Regional Loss Modeling for Highway Network	Peter Gordon	Peter Gordon School of Policy, Planning and Development University of Southern California	Transportation Systems	U=0 G=1 P=0	$20,000	
	1222001 - Building Performance and Loss Measures	James Beck	James Beck Applied Mechanics & Civil Engineering California Institute of Technology	Structural Engineering	U=0 G=1 P=0	$50,010	**Yes**
	1232002 - Regulatory System Implications of Performance Based Regulations	Peter May	Peter May Political Science University of Washington	Public Policy, Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	1242002 - Individual Decisions and Collective Risks	Stephanie Chang	Stephanie Chang Department of Geosciences University of Washington	Risk Analysis	U=0 G=0 P=0	$0	**Yes**
	1252002 - Organizational Decision Processes for EQ Mitigation	Jacqueline Meszaros	Jacqueline Meszaros Management University of Washington	Structural Engineering, Risk Analysis	U=0 G=0 P=0	$0	**Yes**
	1262002 - Assessment of PBEE Testbed Process	John Ellwood	John Ellwood Public Policy University of California, Berkeley	Public Policy, Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 604: Earthquake Risk Decision-making	Dave Seaver	Dave Seaver Sr. Program Manager Battelle Memorial Institute Pacific Northwest Division Kathryn Baker Staff Scientist Battelle Memorial Institute Pacific Northwest Division Patricia Bolton Staff Scientist Battelle Memorial Institute Pacific Northwest Division	Structural Engineering, Operations Research, Public Policy	U=0 G=0 P=0	$173,972	
					Subtotal	$588,982	
Associated Projects							

No Associated Projects Listed		
Subtotal	$0	N/A
Grand Total for 1: Loss Modeling and Decision-Making	$588,982	

Cluster/Thrust	2: Hazard Assessment and Geo-Performance		**Cluster/Thrust Leader**		Ahmed Elgamal	
Personnel: 23 Faculty Members, 1 Undergraduate, 24 Graduate Students, 6 Post Docs, 29 Other Personnel						
Project	**Leader**	**Investigators (name, department, university)**	**Disciplines Involved**	**Number of Students and Post Docs**	**Current-Year Budget**	**Proposed Year 6 Activity?**
Core Projects						
2202001 - Simulation of Ground Deformation in OpenSees	Ahmed Elgamal	Ahmed Elgamal Structural Engineering University of California, San Diego	Geotechnical Engineering	U=0 G=1 P=1	$100,000	**Yes**
2212001 - 3D Soil Simulation Models in OpenSees	Boris Jeremic	Boris Jeremic Civil & Environmental Engineering University of California, Davis	Geotechnical Engineering	U=0 G=2 P=0	$55,000	**Yes**
2222001 - Performance of Improved Ground	Nicholas Sitar	Gregory Fenves Civil & Environmental Engineering University of California, Berkeley Nicholas Sitar Civil & Environmental Engineering University of California, Berkeley	Geotechnical Engineering	U=0 G=2 P=0	$40,000	**Yes**
2232001 - Field Test Data and Simulation of Pier Foundations	Nicholas Sitar	Nicholas Sitar Civil & Environmental Engineering University of California, Berkeley	Geotechnical Engineering	U=0 G=1 P=0	$40,000	
2242001 - Identification and Prediction of Performance-Related Ground Motion	Jonathan Bray	Jonathan Bray Civil & Environmental Engineering University of California, Berkeley	Geotechnical Engineering	U=0 G=1 P=0	$25,000	

	2252001 - Empirical Characterization of Basin Effects on Site Response	Jonathan Stewart	Jonathan Stewart Civil & Environmental Engineering University of California, Los Angeles	Geotechnical Engineering	U=0 G=1 P=0	$50,000	**Yes**
	2262001 - Performance of Shallow Foundations	Bruce Kutter	Bruce Kutter Civil & Environmental Engineering University of California, Davis	Geotechnical Engineering	U=0 G=1 P=0	$70,000	**Yes**
	2272001.1 - Performance of Shallow Foundations	Geoff Martin	Geoff Martin Civil Engineering University of Southern California	Geotechnical Engineering	U=0 G=0 P=0	$30,000	**Yes**
	2272001.2 - Performance of Shallow Foundations	Tara Hutchinson	Tara Hutchinson Civil & Environmental Engineering University of California, Irvine	Geotechnical Engineering	U=0 G=1 P=0	$40,000	**Yes**
	2282001 - Effects of Uncertainties on EDPs	Steve Kramer	Steve Kramer Civil Engineering University of Washington	Geotechnical Engineering	U=0 G=1 P=0	$30,000	
	2292001 - Evaluation of Post-Liquefaction Residual Strength and Stress-Deformation Behavior	Juan Pestana	Juan Pestana Civil & Environmental Engineering University of California, Berkeley Raymond Seed Civil & Environmental Engineering University of California, Berkeley	Geotechnical Engineering	U=0 G=1 P=0	$10,000	
	2302001 - OpenSees Implementation and Validation of P-Y and T-Z Models to Simulate Nonlinear Pier Response	Juan Pestana	Gregory Fenves Civil & Environmental Engineering University of California, Berkeley Juan Pestana Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=0 G=0 P=1	$15,000	

2312001 - Simulation of Soil-Foundation-Structure Interaction of Deep Foundations	Ross Boulanger	Boris Jeremic Civil & Environmental Engineering University of California, Davis Ross Boulanger Civil & Environmental Engineering University of California, Davis	Geotechnical Engineering	U=1 G=3 P=0	$50,000	**Yes**
2322001 - Ground Motions for Testbeds	Paul Somerville	Paul Somerville Seismologist URS Corporation	Geotechnical Engineering	U=0 G=0 P=0	$30,000	
2332002 - Workshop	Ahmed Elgamal	Ahmed Elgamal Geotechnical Engineering University of California, San Diego	Geotechnical Engineering	U=0 G=0 P=0	$0	**Yes**
2342002 - Development of Full-scale Pile-Soil Interaction Data Sets for use in PEER OpenSees Efforts	Scott Ashford	Scott Ashford Geotechnical Engineering University of California, San Diego	Geotechnical Engineering	U=0 G=0 P=0	$0	**Yes**
2352002 - Propagation of Uncertainties due to Geotechnical Properties and Models	TBA	To Be Assigned To Be Assigned To Be Assigned	Geotechnical Engineering	U=0 G=0 P=0	$0	**Yes**
2362002 - Spatial Definition of Ground Motions for OpenSees Simulations	TBA	To Be Assigned To Be Assigned To Be Assigned	Geotechnical Engineering, Geology	U=0 G=0 P=0	$0	**Yes**
Lifelines 1A03: Using 3D Ground Motion Simulations to Estimate Basin Effects for Engineering Purposes	Steven Day	Steven Day Seismologist San Diego State University	Seismology	U=0 G=0 P=0	$0	**Yes**
Lifelines 1C03: Rupture Model of the Duzce, Turkey EQ	Paul Somerville	Paul Somerville Seismologist URS Corporation	Seismology	U=0 G=1 P=0	$49,947	
Lifelines 1C08: Physically Based Source Input for Strong Ground Motion Simulation	Gregory Beroza	Gregory Beroza Department of Geophysics Stanford University	Seismology	U=0 G=0 P=0	$0	**Yes**

	Lifelines 1C09: Working Group for Next Generation Attenuation	TBA	To Be Assigned To Be Assigned To Be Assigned	Seismology	U=0 G=0 P=0	$0	**Yes**
	Lifelines 1D02: Numerical Simulation of Experimental Models for Directivity Effects	Steven Day	Steven Day Department of Geosciences San Diego State University Yuehua Zeng Department of Geosciences University of Nevada, Reno	Seismology	U=0 G=0 P=0	$120,042	
	Lifelines 1E06: Seismic Moment Tensors & Finite-Source Analysis of Chi-Chi	Doug Dreger	Doug Dreger Earth & Planetary Science University of California, Berkeley	Seismology	U=0 G=1 P=0	$44,899	
	Lifelines 1E07: Comparison of Ground Motion Characteristics between Taiwan and California	TBA	To Be Assigned To Be Assigned To Be Assigned	Seismology	U=0 G=0 P=0	$0	**Yes**
	Lifelines 1F01: Development of a Design Ground Motion Library	TBA	To Be Assigned To Be Assigned To Be Assigned	Seismology, Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 1G00: Parameterization of Non-Stationary Time Histories	Paolo Bazzurro	Paolo Bazzurro Principal Engineer Applied Insurance Research	Seismology	U=0 G=0 P=0	$65,139	
	Lifelines 1J01: Surface Fault Rupture Design Models: Hazard Model Inputs	David Schwartz	David Schwartz Seismologist US Geological Survey	Seismology	U=0 G=0 P=1	$138,368	
	Lifelines 1J02: Surface Fault Rupture Design Models: Hazard Models	Mark Petersen	Arthur Frankel Research Geophysicist US Geological Survey Mark Petersen Seismologist US Geological Survey	Seismology	U=0 G=0 P=0	$20,000	
			Badie Rowshandel Senior Seismologist California Department of Conservation Bill Bryant Senior Geologist				

	Lifelines 1J03: Surface Fault Rupture Design Models: Statewide Mapping Products	Chris Wills	California Department of Conservation Chris Wills Supervising Geologist California Department of Conservation Tianqing Cao Senior Seismologist California Department of Conservation	Seismology, Geology	U=0 G=0 P=0	$50,000	
	Lifelines 2A02d: Coordination of SMA Site Data from Taiwan: Phase 1	Robert Nigbor	Robert Nigbor Civil Engineering University of Southern California	Geotechnical Engineering	U=0 G=1 P=1	$90,000	
	Lifelines 2C01: Application of SASW Techniques for Site Characterization	Ken Stokoe	Ken Stokoe Civil Engineering University of Texas at Austin	Geotechnical Engineering	U=0 G=1 P=1	$80,000	**Yes**
	Lifelines 2D01: Vertical Geotechnical Array Database	TBA	To Be Assigned To Be Assigned To Be Assigned	Geotechnical Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 2D02: Seismological Analysis of Vertical Geotechnical Array Data	TBA	To Be Assigned To Be Assigned To Be Assigned	Seismology	U=0 G=0 P=0	$0	**Yes**
	Lifelines 2G01a: Refinement of Califration Sites for Non-linear Models	Jonathan Stewart	Jonathan Stewart Geotechnical Engineering University of California, Los Angeles	Geotechnical Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 2G02: Nonlinear Site Response Calibration Studies	TBA	To Be Assigned To Be Assigned To Be Assigned	Geotechnical Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 2K01: Workshop on Ground Motions for Treasure Island National Geotechnical Experimental Site	Pedro De Alba	Pedro De Alba Civil Engineering University of New Hampshire	Geotechnical Engineering	U=0 G=0 P=0	$30,000	
	Lifelines 3A02: Liquefaction Site Characterization in Taiwan	Jonathan Stewart	Jonathan Stewart Civil & Environmental Engineering University of California, Los	Geotechnical Engineering	U=0 G=1 P=0	$78,217	

			Angeles				
	Lifelines 3A04: Update Database for Liquefaction Data	Jean-Pierre Bardet	Jean-Pierre Bardet Civil Engineering University of Southern California	Geotechnical Engineering	U=0 G=1 P=1	$24,385	
	Lifelines 3C01: Analytical Liquefaction Deformation Model Development	TBA	To Be Assigned To Be Assigned To Be Assigned	Geotechnical Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 3D03: Probabilistic Liquefaction Assessment by Shear Wave Velocity	R. Kayen	Raymond Seed Civil & Environmental Engineering University of California, Berkeley Rob Kayen Researcher US Geological Survey	Geotechnical Engineering	U=0 G=0 P=0	$47,450	
	Lifelines 3F01: Performance of Lifelines Subjected to Lateral Spreading: Full-Scale Experiment	Scott Asford, Ahmed Elgamal, Chia-Ming Uang	Ahmed Elgamal Structural Engineering University of California, San Diego Chia-Ming Uang Structural Engineering University of California, San Diego Scott Ashford Structural Engineering University of California, San Diego	Geotechnical Engineering	U=0 G=2 P=0	$622,597	
	Lifelines 3G01: Pilot Application of Regional Models for Ground Deformation Due to Liquefaction	K. Knudsen	Chuck Real Supervising Geologist California Division of Mines & Geology Keith Knudsen Geologist California Division of Mines & Geology Mark DeLisle Senior Engineering Geologist California Division of Mines & Geology	Geotechnical Engineering, Geology	U=0 G=2 P=0	$103,999	

Lifelines 607: Working Group for Validation of Probablistic Seismic Hazard Computer Programs	Ivan Wong	Ivan Wong Seismologist URS Corporation	Seismology	U=0 G=0 P=0	$73,699	
				Subtotal	$2,223,742	
Associated Projects						
No Associated Projects Listed						
				Subtotal	$0	N/A
Grand Total for 2: Hazard Assessment and Geo-Performance					$2,223,742	

Cluster/Thrust	3: Global Assessment and Design Methodology		**Cluster/Thrust Leader**		Helmut Krawinkler	
Personnel: 13 Faculty Members, 4 Undergraduates, 12 Graduate Students, 0 Post Docs, 0 Other Personnel						
Project	**Leader**	**Investigators (name, department, university)**	**Disciplines Involved**	**Number of Students and Post Docs**	**Current-Year Budget**	**Proposed Year 6 Activity?**
Core Projects						
3162001 - International Workshop on Performance-Based Earthquake Engineering	Jack Moehle	Jack Moehle Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=0 G=0 P=0	$40,000	**Yes**
3172001 - Methodology for Selection in Input Ground Motions for PBEE and Propagation of Uncertainties for IM to EDP	C. Allin Cornell	C. Allin Cornell Civil Engineering Stanford University	Structural Engineering	U=0 G=1 P=0	$70,000	**Yes**
3182001 - Bridge Fragility and Post Earthquake Capacity	Bozidar Stojadinovic	Bozidar Stojadinovic Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=1 G=1 P=0	$50,000	**Yes**
3192001 - Engineering Assessment Methodology	Helmut Krawinkler	Helmut Krawinkler Civil Engineering Stanford University	Structural Engineering	U=0 G=2 P=0	$90,000	**Yes**
3202001 - Relating Structural Collapse and	C. Allin Cornell	C. Allin Cornell Civil Engineering Stanford University	Structural Engineering	U=0 G=0	$20,000	

	Casualties				P=0		
	3212001 - Seismic Hazard Simulation of Bay Area Highway Network Transportation Analysis	Anne Kiremidjian	Anne Kiremidjian Civil Engineering Stanford University	Structural Engineering, Transportation Network	U=0 G=1 P=0	$70,000	**Yes**
	3222001 - Seismic Hazard Simulation of Bay Area Highway Network Transportation Analysis	James Moore	James Moore Civil Engineering University of Southern California	Transportation Systems	U=0 G=2 P=0	$70,000	**Yes**
	3242001 - Life Sciences Testbed Simulation	Khalid Mosalam	Khalid Mosalam Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=1 G=1 P=0	$69,568	**Yes**
	3252001 - I-880 Testbed Simulation	Sashi Kunnath	Boris Jeremic Civil & Environmental Engineering University of California, Davis Sashi Kunnath Civil & Environmental Engineering University of California, Davis	Structural Engineering, Geotechnical Engineering	U=2 G=2 P=0	$50,000	**Yes**
	3262001 - Coordinate PEER Methodology Testbed Research	Keith Porter	John Hall Civil Engineering California Institute of Technology Keith Porter Civil & Environmental Engineering California Institute of Technology	Structural Engineering, Risk Analysis	U=0 G=0 P=0	$103,200	**Yes**
	3272001 - Van Nuys Simulation	Laura Lowes	Laura Lowes Civil & Environmental Engineering University of Washington	Structural Engineering	U=0 G=2 P=0	$70,000	**Yes**
	3282001 - Probabilistic Vector-Valued Ground Motion Intensity Measures and Engineering Demand Measures for the PEER	C. Allin Cornell	C. Allin Cornell Civil Engineering Stanford University	Structural Engineering	U=0 G=0 P=0	$50,000	**Yes**

Van Nuys Holiday Inn PBEE Testbed						
3292001 - Evaluation and Assessment of PBEE Methodology	Jon Heintz	Jon Heintz Associate Degenkolb Engineers	Structural Engineering	U=0 G=0 P=0	$20,000	**Yes**
3302002 - Formalization of Assessment Methodology	TBA	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
3312002 - Design Methodology Framework	TBA	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
Lifelines 507: Building Specific Fragility Curves	C. Allin Cornell	C. Allin Cornell Civil & Environmental Engineering Stanford University	Structural Engineering	U=0 G=2 P=0	$0	**Yes**
				Subtotal	$772,768	
Associated Projects						
No Associated Projects Listed						
				Subtotal	$0	N/A
Grand Total for 3: Global Assessment and Design Methodology					$772,768	

Cluster/Thrust	4: Simulation and Information Technologies		**Cluster/Thrust Leader**		Gregory Fenves	
Personnel: 10 Faculty Members, 0 Undergraduates, 8 Graduate Students, 0 Post Docs, 4 Other Personnel						
Project	**Leader**	**Investigators (name, department, university)**	**Disciplines Involved**	**Number of Students and Post Docs**	**Current-Year Budget**	**Proposed Year 6 Activity?**
Core Projects						
4102001 - PEER Analysis Platform for Demand Simulation	Gregory Fenves	Filip Filippou Civil & Environmental Engineering University of California, Berkeley Gregory Fenves Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=0 G=1 P=0	$100,000	**Yes**
		Gregory Fenves				

	4112001 - Structural Performance Database	Jack Moehle	Civil & Environmental Engineering University of California, Berkeley Jack Moehle Civil & Environmental Engineering University of California, Berkeley Marc Eberhard Civil Engineering University of Washington	Structural Engineering, Information Systems	U=0 G=0 P=0	$75,000	
	4122001 - Development and Validation of Performance Models	Greg Deierlein	Greg Deierlein Civil Engineering Stanford University	Structural Engineering	U=0 G=2 P=0	$90,000	**Yes**
	4132001 - Computational Reliability for Design	Joel Conte	Joel Conte Structural Engineering University of California, San Diego	Structural Engineering	U=0 G=3 P=0	$50,000	**Yes**
	4142001 - Computational Reliability Tools for Design	Armen Der Kiureghian	Armen Der Kiureghian Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=0 G=1 P=0	$50,000	**Yes**
	4152001 - Data Management for OpenSees Simulations	Kincho Law	Kincho Law Civil & Environmental Engineering Stanford University	Structural Engineering	U=0 G=1 P=0	$60,000	**Yes**
	4162002 - RC Joints and Subassemblies Database	TBA	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	4172002 - Applications of Reliability for PEER Framing Equation	TBA	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	4182002 - Advanced Visualization for Seismic Performance	Mike Bailey	Mike Bailey Civil Engineering San Diego State University	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 2L01: Archiving and Dissemination of Geotechnical Data	J. Carl Stepp	J. Carl Stepp COSMOS University of California, Berkeley	Geotechnical Engineering, Information Management	U=0 G=0 P=0	$45,208	
	Lifelines 2L02: Archiving and Dissemination of	J. Carl Stepp	J. Carl Stepp COSMOS University of California, Berkeley	Geotechnical Engineering, Information	U=0 G=0	$0	**Yes**

Project	Leader	Investigators (name, department, university)	Disciplines Involved	Number of Students and Post Docs	Current-Year Budget	Proposed Year 6 Activity?
Geotechnical Data: Pilot Database			Management	P=0		
				Subtotal	$470,208	
Associated Projects						
Large-Scale Seismic Performance of Urban Regions	Gregory Fenves	Bozidar Stojadinovic Civil & Environmental Engineering University of California, Berkeley Gregory Fenves Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=0, G=1, P=0	$128,062	N/A
				Subtotal	$128,062	N/A
Grand Total for 4: Simulation and Information Technologies					$598,270	

Cluster/Thrust	5: Structural and Non-Structural Performance		**Cluster/Thrust Leader**		Stephen Mahin	
Personnel: 16 Faculty Members, 7 Undergraduates, 14 Graduate Students, 1 Post Doc, 9 Other Personnel						
Project	**Leader**	**Investigators (name, department, university)**	**Disciplines Involved**	**Number of Students and Post Docs**	**Current-Year Budget**	**Proposed Year 6 Activity?**
Core Projects						
5242001 - Performance of Building Nonstructural Systems	Eduardo Miranda	Eduardo Miranda Civil & Environmental Engineering Stanford University	Structural Engineering	U=0 G=1 P=0	$60,000	**Yes**
5252001 - RC Frame Validation Tests	Jack Moehle	Jack Moehle Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=0 G=2 P=0	$100,000	**Yes**
5262001 - RC Joint Component Validation & Analyses	Dawn Lehman	Dawn Lehman Civil & Environmental Engineering University of Washington John Stanton Civil Engineering University of Washington Laura Lowes Civil & Environmental Engineering University of Washington	Structural Engineering	U=1 G=1 P=0	$80,000	
5272001 - Bridge Bent		Steve Mahin		U=1		

	Shaking Table Validation Tests	Steve Mahin	Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	G=1 P=0	$100,000	**Yes**
	5282001 - Database and Acceptance Criteria for Column Tests,couple database effort	Marc Eberhard	Marc Eberhard Civil & Environmental Engineering University of Washington	Structural Engineering	U=0 G=1 P=0	$70,000	**Yes**
	5292001 - Performance Characterization for Floor- and Bench-Mounted Equipment	Tara Hutchinson	Gerard Pardoen Civil & Environmental Engineering University of California, Irvine Roberto Villaverde Civil & Environmental Engineering University of California, Irvine Tara Hutchinson Civil & Environmental Engineering University of California, Irvine	Structural Engineering	U=2 G=1 P=1	$60,000	**Yes**
	5302001 - Performance Characteristics of Building Contents	Nicos Makris	Nicos Makris Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=1 G=1 P=0	$80,000	**Yes**
	5312002 - Development of Advanced Performance RC Frames	TBA	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	5322002 - Performance of Nonstructural Partition Walls	TBA	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 401b: Analytical Models for Electrical Equipment Connected by Rigid Buses	Armen Der Kiureghian	Armen Der Kiureghian Civil & Environmental Engineering University of California, Berkeley	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 402: Substation Equipment Interaction - Experimental Models of Rigid Bus Connectors	Andre Filiatrault	Andre Filiatrault Structural Engineering University of California, San Diego	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 403a: Substation Equipment Interaction - Flexible Buses	Andre Filiatrault	Andre Filiatrault Structural Engineering University of California, San Diego	Structural Engineering	U=1 G=1 P=0	$82,153	
	Lifelines 403b: Substation Equipment	Armen Der	Armen Der Kiureghian Civil & Environmental Engineering		U=0		

	Interaction - Flexible Buses	Kiureghian	University of California, Berkeley	Structural Engineering	G=1 P=0	$51,046	
	Lifelines 404: Improvements to Modeling of Substation Equipment	Gerard Pardoen	Gerard Pardoen Civil & Environmental Engineering University of California, Irvine	Structural Engineering	U=2 G=2 P=0	$65,000	**Yes**
	Lifelines 405: Test Protocols for Seismic Qualification of Disconnect Switches	TBA	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 406: Seismic Qualification Requirement for Transformer Bushings	Andre Filiatrault	Andre Filiatrault Structural Engineering University of California, San Diego	Structural Engineering	U=1 G=1 P=0	$110,000	
	Lifelines 411: Qualification and Fragility Testing of 500kV Disconnect Switch	To be assigned	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 412: Feasibility of Base Isolation of Electric Substation Equipment	To be assigned	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 504: Development of an Improved Methodology for Buildings with Rigid Walls and Flexible Diaphragms	James Anderson	James Anderson Civil Engineering University of Southern California	Structural Engineering	U=0 G=1 P=0	$64,993	
	Lifelines 507b: Application of Advanced Assessment Guidelines to Structures	To be assigned	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 509: Evaluation and Application of Concrete Tilt-up Assessment Methodologies	To be assigned	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 6D01: Cost Sensitivity of Bridges to Design Ground Motions	To be assigned	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0 P=0	$0	**Yes**
	Lifelines 703: Rapid Post-Earthquake Documentation of	To be assigned	To Be Assigned To Be Assigned To Be Assigned	Structural Engineering	U=0 G=0	$0	**Yes**

	Substation Damage				P=0		
					Subtotal	$923,192	
Associated Projects							
No Associated Projects Listed							
					Subtotal	$0	N/A
Grand Total for 5: Structural and Non-Structural Performance						$923,192	

Table 2: Research Program Organization and Effort Totals	Current-Year Budget	
Total, Core Projects	$4,978,892	
Total, Associated Projects	$128,062	
Grand Total, All Projects	$5,106,954	

LEGEND:

U Number of Undergraduate Students

G Number of Graduate Students

P Number of Postdoctoral Fellows

2.2.1 Overview of 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 performance-based earthquake engineering. 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 performance-based earthquake engineering, 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 of structural and nonstructural systems. 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.

2.1.1.1 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 Task Leaders to provide close oversight and coordination of those projects funded through the lifelines program. Being affiliated with the Business and Industry Partners, these task leaders provide a natural technology transfer mechanism with the sponsoring organizations. Professor Fenves, *Assistant Director for the Lifelines Program*, and Dr. Michael Riemer, *Program Manager for the PEER Lifelines Program* provide overall coordination of the program. Task 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 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 tasks are coordinated through the associated thrust areas.

2.1.1.2 External Research Collaborations

The PEER research program is involved with a number of collaborations with outside centers and agencies, professional societies, and individual investigators. Some highlights of PEER's external research collaborations include:

- **MAE and MCEER:** Jointly authored by the three NSF-EERCs, Volume III of the PEER Year 4 annual report (April 2001) provides a detailed background and summary of research collaborations between PEER and the other two centers. Collaboration between individual researchers and research groups has been ongoing, and a joint planning meeting between the three centers is scheduled for July 2002, where we will discuss collaboration on ground motion selection, liquefaction and ground deformations, performance databases and simulation, and social science considerations.

One area of very active collaboration is in the social sciences. Peter May (Thrust Area 1 co-leader) has been instrumental in arranging meetings for research exchanges related to earthquake risk decision-making. One result of this has been joint collaboration on a FEMA-funded project aimed at providing guidelines for seismic safety advocates.

Another area of active collaboration has been on the earthquake risks and response of highway networks and bridge fragility models. Both PEER and MCEER-FHWA have active projects on the seismic performance of highway networks, which involves seismic hazard characterization (both ground motions and ground deformations), bridge and roadway performance (fragilities), and the impact of bridge and roadway damage on the traffic network. As a result of efforts during the past year, MCEER and PEER are collaborating with Caltrans on developing bridge fragility functions for retrofitted bridges and network simulations of the San Francisco Bay Area highway network.

- **SCEC:** SCEC's research on earthquake source modeling and ground motion characterization in southern California ties directly into PEER's PBEE methodology. SCEC and PEER have a formal collaboration agreement, through which Dr. Paul Somerville (engineering seismologist with URS) is funded as a liaison between SCEC and PEER. Somerville has been instrumental in developing the ground motion libraries used for the PEER testbed studies, and he and Allin Cornell have a jointly funded PEER-SCEC project to study vector-based hazard characterization. PEER and SCEC are currently pursuing other opportunities for jointly funded projects, which bridge the boundary between seismic hazard characterization and geotechnical and structural earthquake engineering.
- **NCREE:** As part of a broader effort to build international research collaborations among Pacific Rim countries, PEER has entered into a formal collaboration agreement with NCREE in Taipei. Following the 1999 Chi-Chi earthquake, the two centers initiated collaborative research to utilize recorded ground motions and data from follow-up studies to investigate damage to bridges and buildings. One important component of the cooperative research was PEER-Lifelines co-funding of several NSF-supported projects in follow-up studies on the Chi-Chi earthquake. Other initiatives have been on large-scale testing of reinforced concrete and composite steel-concrete structures.
- **US-JAPAN:** PEER researchers and member institutions have a long history of collaboration with Japan, and PEER has capitalized on these connections to formalize research collaboration on several fronts. PEER has co-sponsored three annual workshops on performance-based design of reinforced concrete buildings, with a fourth workshop planned for October 2002 in Kyoto. The PEER Lifelines program has also co-funded studies on ground deformations and liquefaction of mutual interest to US and Japanese utility companies and geotechnical researchers.
- **ATC 58:** FEMA recently funded the Applied Technology Council for a project called ATC 58 – Performance-Based Seismic Design Considerations. This project is intended to refine understanding of performance considerations and to reassess the appropriateness of long range planning for seismic performance design guidelines. PEER is contributing to this effort through involvement of two PEER research committee members on the ATC 58 project management committee. This activity holds promise as a very important vehicle for translating PEER research into practice.

2.1.2 Thrust Area 1 - Loss Modeling and Decision-Making

2.1.2.1 TA 1 Goals

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, and to contribute to the systems integration as it relates to the implementation and evaluation of PBEE. This area contributes to the definition of performance goals and measures, to evaluation of costs of earthquakes, to strategies for disseminating performance-based engineering tools and frameworks, and to the evaluation of performance-based engineering. These topics address the "front end" (design) and "back end" (implementation and evaluation) of PEER's development of performance-based earthquake engineering. 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 design and by integration of the socio-economic component with engineering considerations.

2.1.2.2 TA 1 Strategic Plan

The strategic plan for this thrust area (Figure 2.11) calls for continuing research components: (1) decision-making – contribution to fundamental knowledge at the basis for PBEE decisions, the framing of decisions, and the presentation of information; (2) economic tools as enabling technology for evaluating performance-based design — development of tools for use in decision-making and in evaluating the overall impact of performance-based design; (3) modeling of losses and costs – understanding as fundamental knowledge of the costs associated with structural and nonstructural damage to facilities as critical for understanding the financial consequences of different levels of damage; and (4) implementation of performance-based engineering tools and frameworks — identification of obstacles (beyond adoption) to putting performance-based design in place and to using the tools and frameworks developed by PEER. Beginning with Year 6, the PEER efforts in this area will place stronger emphasis on practical lessons from the testbeds for decision-making and economic analysis and upon broader implications for the regulatory system.

2.1.2.3 TA 1 Critical Mass and Level of Effort

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

2.1.2.4 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 performance-based tools and frameworks, rather than specific outputs. Significant research contributions of the loss modeling and decision-making component of PEER research include the following:

- *Decision Considerations:* Several prior year projects led to better understanding of the conceptual underpinnings for thinking about performance-based frameworks, including case information on approaches to seismic retrofit within the University of California system and questions related to risk management. During Year 5, projects have begun to focus more decision processes to risk mitigation by corporations and lifelines organizations (May, Meszaros, and Seaver115, 117, and LL604).
- *Loss Modeling:* A report has been completed to assess nonstructural damage as a key component of downtime for a university laboratory building (Comerio 119 & 120), which is representative of broader classes of university and industrial research facilities. This project led to the establishment of laboratory equipment tests under Thrust Area 5 (Hutchinson, Makris, 529, 530), information from which is being incorporated into a probabilistic loss model geared to the Life Sciences testbed (Beck 122). A detailed probabilistic framework for loss modeling for structural (Miranda 118) and nonstructural damage (Miranda 524) have been developed in the context of the Van Nuys testbed, and work is ongoing to develop detailed damage-repair cost data for these components.

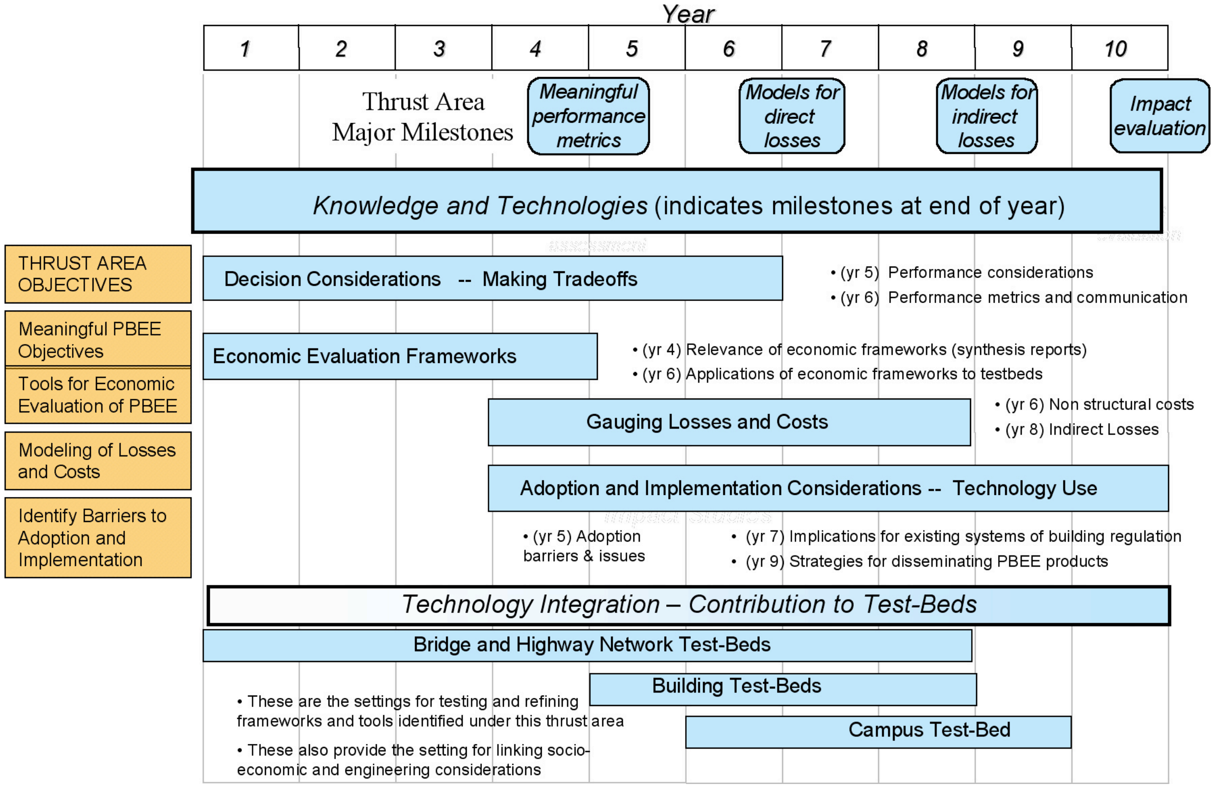

Fig. 2.11 Strategic Plan - Loss modeling and decision-making

- *Economic Evaluation:* Previously, a framework has been developed for economic evaluation of seismic improvements for port facilities, and this has recently been generalized to a benefit-cost evaluation model for PBEE (Zerbe 116). Projects (Zerbe and Meszaros 116, 117) have over the past two years focused on learning from the Nisqually earthquake related to business decision-making and economic losses. This real-world data set has been incorporated together with financial investment-assessment models to ascertain the pertinence of these models to earthquake mitigation.
- *Policy, Regulation, and Impediments:* Prior year accomplishments include a PEER report on municipal code enforcement capabilities in the Western U.S. More recently, projects related to policy (May 115) have focused on understanding of key barriers to implementation of new seismic mitigation techniques and models, such as PBEE. Included with this has been a historical case-study review of the experience in introducing other innovations such as seismic isolation technologies and probabilistic load and resistance factor design provisions.

2.1.2.5 TA 1 Future Plans

Activities will be undertaken in Year 6 and subsequent years with respect to each of the four topics of research in this thrust area:

- *Decision-making* – Continued research as part of the lifelines program will focus on decision-making within lifelines organizations that will supplement prior research on decision considerations for earthquake risk management. A continuing direction for this topic is research on presentation of PBEE decision information including attention to ways of communicating tradeoffs and uncertainties in estimates. The goal of this research is to devise effective ways for presenting the results of PBEE analyses. Participation in testbeds will continue to be important for identifying relevant decision considerations and their tradeoffs.

- *Economic evaluation tools* – Work will continue on developing benefit-cost protocols that can be incorporated into the PEER PBEE framework and developing regional economic impact models for understanding the societal impacts of PBEE. Products from this research will be protocols for economic evaluation of decisions concerning individual structures and regional consequences. Participation in testbeds will also be important for integration of this research with the broader PBEE framework.

- *Modeling of losses and costs* – This continues a Year 5 initiative aimed at filling an important gap in understanding of PBEE. Projects aimed at developing information about the dollar value of damages and business interruption associated with different levels of structural and nonstructural damage are being undertaken in conjunction with the testbeds.

- *Implementation considerations* – This is a continuation of research that is aimed at providing a better understanding of the barriers to adoption and implementation of new methodologies or technologies by the engineering and design professions. An important new direction beginning in Year 6 is consideration of the implications of PBEE for the regulatory system more broadly, which will lead to insights about the broader barriers to implementing PBEE innovations.

2.1.3 TA 2 - Hazard Assessment and Geo-Performance

2.1.3.1 TA 2 Goals

The hazard assessment and geo-performance research program is directed toward evaluation of the effect of ground motion hazards, ground response/deformation, and system performance. This thrust area includes elements of ground motion characterization, evaluation of free-field ground response, and evaluation of soil-foundation-structure interaction. The hazard assessment research will consider uncertainties and spatial/temporal variabilities in ground motion, soil conditions, and their influence on performance. The scope is focused on providing direct input into the development of reliability-based global design methodologies, and into improved procedures for demand evaluation and loss estimation. Results of the hazard assessment research, particularly that dealing with evaluation of ground response and soil-foundation-structure interaction, are being implemented into the OpenSees analytical platform.

Studies of ground motions, site response, and ground failure undertaken by others have not been oriented toward multi-level performance prediction, and have generally not included uncertainties and spatial/temporal variabilities. The explicit consideration of these factors, and the focus on soil-foundation-structure interaction, are distinguishing features of PEER's Hazard Assessment thrust area.

2.1.3.2 TA 2 Strategic Plan

The strategic plan for the Hazard Assessment and Geo-Performance thrust area calls for a coordinated sequence of research efforts that will allow geotechnical and ground motion hazards to be realistically accounted for in improved tools and procedures for performance evaluation and performance-based design. The research funded by the Core Program is supplemented by a strong component of hazards and geotechnical research funded by the Lifelines Program, and part of the strategic plan is to optimize resource utilization in both programs. Research efforts consist of one or more individual projects directed toward (1) compilation of relevant information from recent earthquakes (Turkey and Taiwan) and conducting related studies; (2) definition of seismic ground motions; (3) site response and site characterization; (4) improved tools and procedures for ground response prediction with an emphasis on permanent deformation; (5) improved tools and procedures for analysis of soil-foundation-structure systems including permanent ground deformation effects; (6) testing and validation of seismic hazard models and algorithms; and (7) development of performance-based computational (OpenSees) and design procedures for soil-foundation-structure interaction, soil improvement, and foundation remediation.

The strategic plan is illustrated in Figure 2.12. Research in the area of ground motions began in Year 1 and has continued with interaction with earth scientists (both within PEER and through the Southern California Earthquake Center). A strong component of this research places emphasis on establishing regional aspects of ground motions (e.g., site specific motions for the Bridge Testbeds, Somerville 232, motions for Treasure Island Workshop De Alba 2K01), compilation of on-line ground motion databases (http://peer.berkeley.edu/smcat, and the COSMOS Workshop), as well as improved understanding of ground motion characteristics (Bazzurro 1G00), site/basin effects, and uncertainties (Bray, Stewart, Kramer 224, 225, 228). Optimal ground motion intensity measures, i.e., ground motion parameters that correlate well to structural and geotechnical performance, are being identified; attenuation relationships for these parameters are being developed (e.g., Bray 224). To account for cases where more than one ground motion parameter may be required to predict performance, vector-based hazard analysis procedures are being considered. Procedures for selection of design ground motions that are consistent with site-specific hazards are also being developed (Somerville 232). A series of related projects that include in-situ testing (Stokoe 2C01), laboratory modeling of soil stress-strain behavior (Pestana 229), and foundation response (Kutter, Martin 226, 227) are culminating in the implementation of validated constitutive models into OpenSees (Elgamal 220, Jeremic 221). Research on soil-foundation-structure interaction SFSI (Field and Centrifuge) began in Year 2 and will continue through Year 7 (Kutter, Martin, Sitar, Ashford 226, 227.1, 227.2, 223, 3F01). This research effort initially focused on deep foundations toward the development of p-y and t-z elements that are being implemented into OpenSees (Boulanger 231, Pestana 230). The SFSI research is now emphasizing both shallow and foundations and the effects of their response on structural performance. Research to summarize the known performance of improved soils in earthquakes currently continues (Sitar 222) and will further increase in future years. Research in

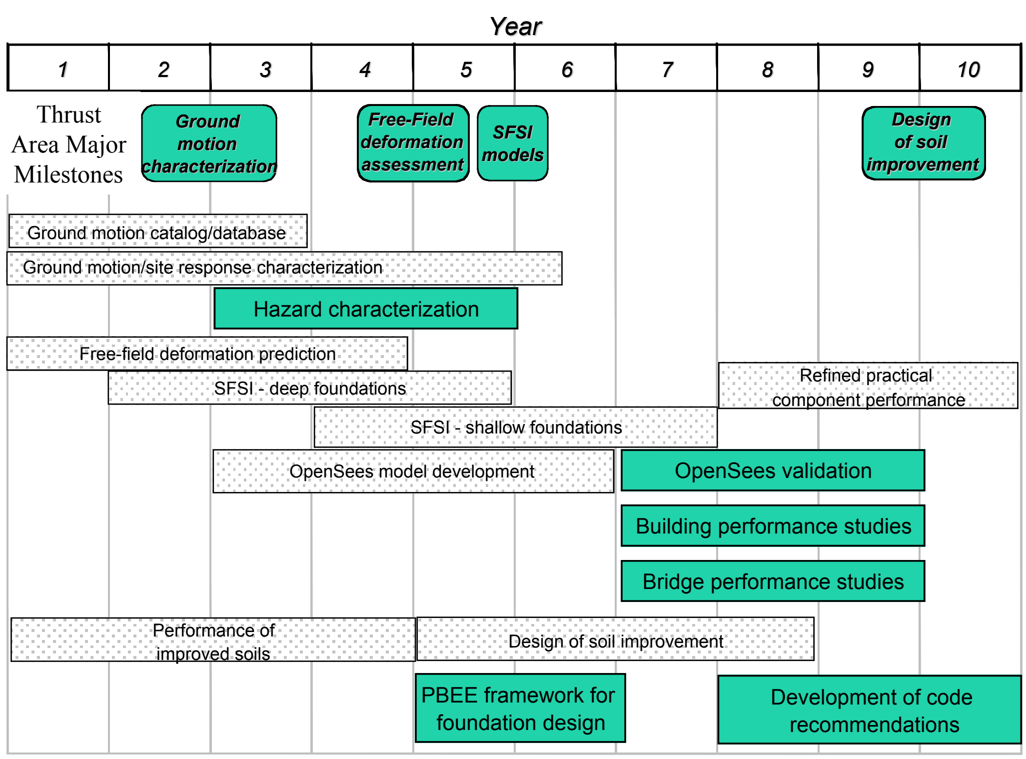

Fig. 2.12 Strategic Plan – Hazard Assessment and Geo-Performance

this area will continue with a goal of establishing performance-based design procedures for soil improvement and foundation remediation (including in-situ and centrifuge experimentation).

Recent seismic events are also being analyzed for information of relevance to seismicity in California. Modeling of seismic source efforts is under way (Somerville 1C03, Dreger 1E06, Beroza 1C08). Such seismic events have increased our ground motion database (http://peer.berkeley.edy/smcat and Nigbor 2A02d), and permitted the compilation of valuable liquefaction related information (Stewart 3A02, Bardet 3A04, Kayen 2D03). Comparison between the characteristics of seismic motions in California and those recorded elsewhere will be undertaken (task 2L01).

Seismic hazard particularly in California is receiving special attention. Validation of numerical simulation models for directivity effects (Day 1D02) has involved interaction with SCEC. Ground deformation effects are investigated in terms of fault rupture hazard models (Schwartz 1J01, Petersen 1J02, Chris 1J03), and liquefaction hazard models (Knudsen 3G01). Practical seismic hazard probabilistic tools are being compared and further validated (Wong Lifelines 607).

2.1.3.3 TA 2 Critical Mass and Level of Effort

Achieving the objectives of this thrust area requires both experimental and analytical contributions. These researchers have access to high-quality, and in some cases unique, experimental equipment and facilities. Where appropriate, geotechnical researchers are working closely with engineering seismologists from the Southern California Earthquake Center (SCEC), private practice, and foreign entities, particularly in site characterization and development of ground motion catalogs. Researchers who are developing improved ground motion excitation scenarios, calibrated soil constitutive relationships, and soil-foundation-structure interaction models are working closely with the OpenSees developers to add geotechnical capabilities to that platform. Researchers also are interacting with practitioners through the various test bed projects.

2.1.3.4 TA 2 Research Advances and Deliverables

Hazard Assessment and Geo-Performance researchers have made significant advances in a number of important areas. Considerable progress has been made in developing improved understanding of the medium- to large-strain behavior of liquefiable soils. These advances have come from experimental work, including laboratory cyclic simple shear testing and centrifuge model testing, and from analytical work aimed at constitutive modeling of liquefaction. This research has produced useful data and first-generation constitutive models that, after implementation into OpenSees, have produced improved predictions of the performance of liquefiable soils. Other projects have developed improved techniques for modeling soil-pile-structure interaction, including coupled lateral (*p*-*y*) and vertical (*t*-*z*) elements, interface elements, and transmitting boundary elements. Models for near-fault pulses and probabilistic models of empirical site response have also been developed. In other projects, field observations are being supplemented by centrifuge model test results in which careful instrumentation is allowing observations of fundamental aspects of soil behavior (e.g., soil-pile interaction, lateral spreading, shallow foundation response, response of improved soils) that are rarely quantified in the field.

Four major three-dimensional, seismological modeling codes have been jointly validated on a series of increasingly complex canonical problems, and are now being applied to the investigation of basin effects and rupture directivity. A wealth of valuable new seismological and geotechnical data from the Turkey and Taiwan earthquakes have also been acquired and processed, and incorporated into improved attenuation relationships. An improved, probability-based method of identifying liquefaction occurrence based on Standard Penetration Testing has been developed, and is being adapted to other in situ testing methods as well.

Much of the developed expertise and methodologies is being directly applied to the PEER Bridge testbeds (Humboldt Bay and I-880). These testbeds are allowing for integration of activities and demonstration of the new practical research outcomes. This work will be the template for conducting seismic probabilistic and performance-based investigations in the coming years on an expanded scale.

2.1.3.5 TA 2 Future Plans

The Year 6 research projects will further focus on the integration of hazard analysis and performance analysis, on the influence of foundation performance on structural performance, on extension of the geotechnical modeling capabilities of the OpenSees analytical platform, and on the initial development of performance-based design procedures for soil improvement. Much attention will be directed toward rendering OpenSees an environment for routine advanced simulation, with integrated probabilistic capabilities.

Hazard analysis research will explore and verify improved intensity measures, i.e., intensity measures that correlate well to both geotechnical and structural aspects of performance. Procedures for selection of hazard-consistent ground motion time histories will also be developed; such time histories are required for performance prediction. These topics, hazard intensity measures and ground motion selection, are closely related to performance assessment methodology development and will be pursued as a shared activity with Thrust Area 3.

The effects of ground deformation and foundation behavior on structural performance remain an important area of investigation. Research to determine the effects of factors such as foundation yielding on structural performance will be conducted. This research will allow determination of the benefits (e.g., reduced structural demands) and drawbacks (e.g., foundation settlement) of designing foundations to allow limited yielding. Projects involving both shallow and deep foundations will be supported, and the research will be further coordinated with OpenSees developments and the Testbed studies.

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. These capabilities include that of 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 analysis. This research will be performed by the team of investigators that has been working on geotechnical aspects of OpenSees; these researchers are also work with engineering seismology and structural engineering colleagues to develop OpenSees soil/foundation models of the Testbed structures.

In the Lifelines area, future work in Hazard Assessment and Geo-Performance will include pilot studies to assess the feasibility of developing regional earthquake ground-deformation maps, and probabilistic design models for fault surface-rupture displacements. These projects will involve the direct participation of state and federal agencies (California Geological Survey and United States Geological Survey) with immediate applications for the results of these studies, and therefore will be poised to implement the potential advancements directly into practice. Other upcoming projects include the simulation and parameterization of rupture directivity effects, which will complement the ongoing experimental work in this area, and which form such an important feature of large magnitude, near-fault ground motions. Further work is also anticipated in characterizing the uncertainties in measuring dynamic soil properties, so that reliability-based models can appropriately account for the possible bias of particular testing methods.

2.1.4 Thrust Area 3 - Assessment and Design Methodologies

2.1.4.1 TA 3 Goals

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

- a methodology that will facilitate the 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 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.

2.1.4.2 TA 3 Research Plan, Milestones, and Deliverables

Figure 2.13 shows the strategic research plan for meeting the goals of the Assessment and Design Methodologies thrust area. The plan involves two overall efforts and four major deliverables over ten years.

The first major effort is the development of a comprehensive *Performance Assessment Methodology*. A test version of this methodology has been completed, and it is planned to have a comprehensive methodology in place by the end of Year 6. The methodology is being subjected to extensive testing in the building and bridge testbeds, which have commenced at the beginning of Year 5.

The time spans of the focus areas that make up this effort are delineated in the upper portion of Figure 2.13. Work in all areas is in progress and will continue at least until the end of Year 6. Much of the effort on “direct losses and loss of function” has been moved to Thrust Area 1 in order to benefit even more from direct interaction with researchers on the socio-economic aspects of the performance assessment and implementation processes. Loss assessment and modeling and propagation of uncertainties are expected to remain the subject of research until the end of Year 8. The last focus area of the performance assessment methodology effort is the development of an engineering approach. The objective is to synthesize the previously developed knowledge to bring it into a format in which it can be delivered to the engineering profession, together with tools that make implementation feasible. This work has started in Year 5. It implies the development of simplified engineering approaches that preserve, to the extent possible, the probabilistic content of the reliability-based formulation.

The second major effort is concerned with the development of a comprehensive *Design Methodology* in which multiple performance objectives are considered in the process of conceiving performance-compliant and cost-effective structural and nonstructural systems. The ongoing research on an engineering approach to performance assessment provides a transition to the focus on design methodology. The present perspective is to perform conceptual design, based on discrete limit states that can be expressed in engineering terminology of forces and deformations, but are reliability-based. Efficiency of design may come into play in an iterative process in which design alternatives are evaluated on a benefit/cost (or relative cost) basis. The last phase of this research is concerned with implementation issues, which need to be addressed to make the PBEE approach a feasible and effective design/evaluation alternative for practicing engineers, and to make PBEE an acceptable and attractive approach for all stakeholders.

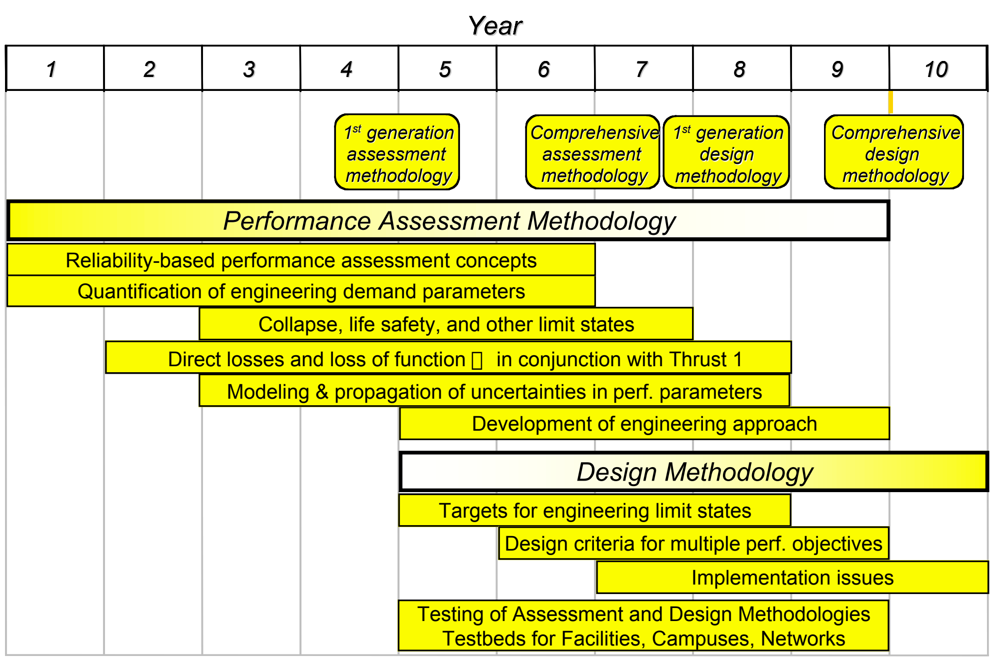

Fig. 2.13 Strategic Plan – Assessment and Design Methodologies

Testing of the performance assessment and design methodologies forms a crucial part of the development effort. For this reason, testbed coordination and projects that focus fully on specific aspects of the testbed effort are incorporated in this thrust area. It is expected that these testbeds, which are briefly described in Section 2.1.1.2(c), will point out shortcomings and gaps of the methodology and tools, and will provide feedback and input to the projects in all thrust areas.

2.1.4.3 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 building and bridge structures. The research team has been put together to cover all these areas of expertise and to assure close interaction with efforts in other thrust areas that are related to methodology development.

The effort during Year 5 is focusing on the quantification of parameters and characterization of uncertainties in the IM and EDP domains (317, 318, 319, and 328), issues related to collapse and life safety (319 and 320), engineering approaches to performance assessment (319 and LL 507), development of fragility curves that encompass the path from IMs to EDPs to DMs (318 and LL 507), testbed-specific projects (324, 325, 326, 327, 328, and 329), and cross-cutting projects on a highway network (321 and 322).

2.1.4.4 TA 3 Research Advances and Deliverables

Most of the research started in late spring or early summer 1998. Thus, the end of the fourth year of research is approaching (early summer 2002). The targets set in the early phases of the Center essentially have been accomplished on time. The steps for a rigorous assessment methodology have been formalized (see Section 2.1.1.2(b)) and are in the documentation stage. 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 of relationships between engineering demand parameters and associated damage and losses (fragility curves, cost functions), and relationships between states of partial or complete collapse and number of casualties.

Much progress has been made in predicting the probability of collapse of structural systems. Deteriorating hysteresis models have been developed, 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 make up the structural system.

A comparatively simple first-order, second-moment scheme has been developed for conducting uncertainty propagation through the random vectors of EDPs and DMs to the DVs in the PEER framing equation. The results are the first and second moments of the DVs, given IM. These can be used with the IM hazard curve to produce mean and variance of each DV, and, with an appropriate distribution assignment, the DV "hazard curve."

2.1.4.5 TA 3 Future Plans

The Year 6 projects in this thrust area will center on three aspects of methodology development. The first focus will be on gaps that have to be closed in order to bring the development of a rigorous performance assessment methodology to completion. The emphasis will be on the identification, quantification, and propagation of uncertainties from IMs to DV, and on the development of an engineering assessment methodology. The second focus will be on the development of a performance-based design methodology, with input from practicing engineers and stakeholders on engineering needs for a design approach, on performance criteria of primary concern to the users, and on the types of work products of primary interest to the design profession. The third focus will be on coordinated testbed efforts, with most of the testbed projects of Year 5 continuing through Year 6, and additional work planned with an emphasis on the application of the performance assessment methodology to the testbeds.

2.1.5 Thrust Area 4 - Simulation and Information Technologies

2.1.5.1 Goals

Thrust Area 4 continues to focus on the development of new simulation capability for structural and geotechnical systems, and their linkages through soil-foundation-structure-interaction, integrating simulation with reliability computation, and incorporation of databases, visualization, networking and other information technologies in performance-based earthquake engineering. These technologies are central to PEER's vision of PBEE, which requires high fidelity simulations to determine demand parameters for systems with highly nonlinear behavior and load redistribution caused by cyclic degradation and the consequences of local failure modes. The PEER research program addresses these simulation needs through a coordinated development of improved models of structural components (in this thrust area and the Structural Performance thrust area) and soils (Hazard Assessment and Geo-performance thrust area). The models are based on mechanics that represent the observed behavior of materials and components, and verified using databases of experimental data. The incorporation of uncertainty in the simulation is essential, in order to provide the capability to propagate uncertainties associated with the earthquake hazard, structural and geotechnical model parameters, and simulation method itself.

As described earlier in Section 2.1.1.3, *OpenSees* is the focal point of PEER's enabling technology for simulation in performance-based earthquake engineering. *OpenSees* is a *framework* designed using object-oriented methods to maximize modularity and extensibility for implementing models for structural behavior, soil and foundation behavior, and damage measures. The framework is a collection of inter-related classes, which for our applications include 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 *OpenSees* software is open source, meaning that all parts of the code are available for students, researchers, engineering professionals, and other users to see, check, track changes, and make contributions. The *OpenSees* website at http://opensees.berkeley.edu has a download center with executables, source code, examples, and documentation. OpenSees is the first web-accessible, open-source software, designed to serve as a community code for earthquake engineering. Currently, more than 200 users/developers (in the U.S. and internationally) have registered on the *OpenSees* website. While OpenSees is primarily motivated by the research needs for performance-based earthquake engineering, we expect it to become a valuable tool for professional engineers.

As community software, *OpenSees* provides an important resource for the National Science Foundation-sponsored George E. Brown, Jr. Network for Earthquake Engineering Simulation. 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 many 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.

2.1.5.2 TA 4 Strategic Research Plan, Milestones and Deliverables

Figure 2.14 shows the strategic research plan for meeting the goals of the Simulation and Information Technologies. The plan involves three overall efforts and four major deliverables over ten years. The three efforts are development of (1) a software framework for advanced simulation, (2) model and simulation methods, and (3) performance databases. As shown in the figure, the major deliverables are the simulation framework, models based on experimental databases, and an advanced computing network utilizing parallel/distributed computers, databases, and scientific visualization.

The Year 4 Site Visit Team cited several weaknesses related to OpenSees and database management, which we have responded to with some changes and new initiatives in Year 5. The stated weaknesses related to (1) lack of documentation and validation of OpenSees; (2) inconsistent perceptions/visions of OpenSees by different researchers; (3) inadequate support for information technology, computer science, and computer visualization, (4) lack of stochastic simulation modules in OpenSees; and (5) unclear plans for development of database management. We believe that advancements made of the past year have addressed these weaknesses, and specific Thrust Area 4 initiatives/accomplishments, which respond to these, are described in this and the following sections.

The first major effort has been the development and maintenance of the OpenSees platform, with continuing improvements, documentation, and development with leading computation and information technologies. Through new version releases of OpenSees, user/developer workshops, and greater integration in the testbeds, considerable progress has been made toward developing a common understanding and vision of OpenSees by the PEER research and industry community. Version 1.0 was released in September 2000 with the launch of the OpenSees website, and we are currently at Version 1.3. All documentation is available on the website, including documents on the overall program usage for users and how to incorporate new modules into the framework. To provide better documentation, additional funding will be provided in Year 6 to support the testbed researchers and expand the documentation. Related to this, PEER has sponsored user/developer workshops at PEER Headquarters (Aug. 2001, Sept.

2002) and two special seminars at the 2002 ASCE Structures Congress in Denver. Each event attracted more than forty attendees.

The next major effort is on demand simulation models and methods. The fundamental research includes structural component modeling with emphasis on non-ductile reinforced concrete columns and joints. The models include path-dependent degradation in strength and stiffness for realistic demand assessment of earthquake performance. These models are used for studying the evolution of damage in a structure under different types of earthquakes and assessing residual capacity of a structure in aftershocks. Researchers in this thrust area work closely with those in the Structural Performance thrust area to develop and validate structural models. Simulation researchers also coordinate closely with the geotechnical engineering researchers in Hazard Assessment and Geo-Performance to develop the models for soils, including liquefaction, foundations, and soil-foundation interfaces. The solution of the governing equations with highly nonlinear, degrading models requires robust strategies for static and dynamic loading. The incorporation of sensitivity computation (through gradients of response with respect to parameters) in the simulation methods is a key step for three important areas within performance-based approaches: (1) reliability computation based on nonlinear simulations, (2) system identification for calibrating simulation models based on data from experimental databases, and (3) optimization for use in performance-based earthquake engineering design methodologies.

The third strategic effort in the thrust area is the development of databases for experimental data and for ground motion data. 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. In addition to validation of material and component models, OpenSees is being used in

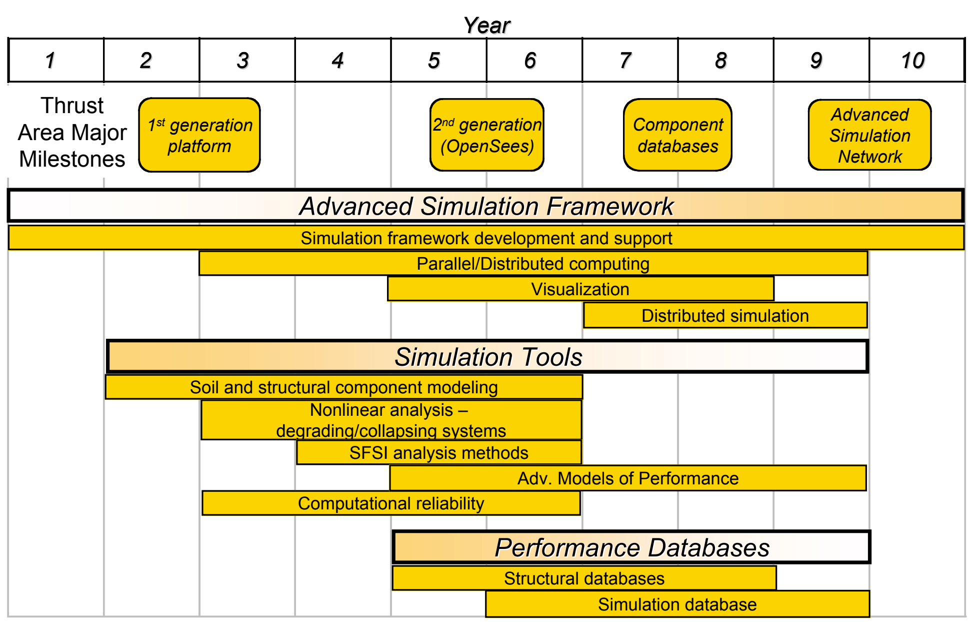

Fig. 2.14 Strategic Plan – Simulation and Information Technologies

comprehensive validation of the system behavior of buildings and bridges in the testbeds described elsewhere in this report.

2.1.5.3 Critical Mass and Level of Effort

The research team for the thrust area includes experts on modeling reinforced concrete components and simulation methods for such models. The researchers work with Structural Performance thrust researchers in developing the models using experimental data. Other researchers are well known for their accomplishments in 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 four of the testbed projects now under way, 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 Year 4 renewal site visit report was inadequate support for information technology, computer science, and visualization. We agree that greater involvement of computer science (CS) specialists in the development of OpenSees would be advantageous, and we are working to leverage existing resources to do this. Specific steps we are taking in this regard are as follows: (1) We will continue to tap into CS expertise through those PEER investigators who have stronger interests and connections to CS and through our graduate student researchers, many of whom are pursuing doctoral minors in CS; (2) We are initiating a scientific visualization project with Dr. Michael Bailey of the San Diego Super Computing (SDSC), which builds upon previous collaboration between Prof. Fenves and Elgamal and SDSC; and (3) We will continue to leverage OpenSees with collaborative external funding, such as a project now under way between PEER, Carnegie Mellon, and Mississippi State University to develop simulation models for the impacts of earthquakes on entire urban region and another NSF ITR program at Berkeley on CITRIS (Center for Information Technology in the Interest of Society), which leverages the PEER developments, including OpenSees, in simulation and databases for new sensing, communication, and decision-making for response to natural and man-made disasters.

2.1.5.4 Research Advances and Deliverables

In the area of structural modeling, Year 5 has seen the completion of models for beam-column elements for reinforced concrete members, including a library of constitutive models for concrete and steel. The hierarchical design of the models provides great flexibility in representing element, section, and material behavior. Recent extensions to the modeling capabilities include: (1) the inclusion of large-displacements with co-rotational and updated Lagrangian approaches (Filippou, Deierlein, 410 412), (2) strength and stiffness degrading generalized hinge models for beam-columns (Deierlein 412), (3) beam-column models for shear and shear-flexure interaction (Filippou, Fenves, Moehle, 410, 525), and (4) a new model for beam-column joint that represents the effects of joint shear, bond slip, and yield penetration (Lowes, prior year project and 526). These models have been verified by experimental data and other solutions, and are now being applied in the testbed studies and new system validation tests from Thrust Area 5.

With the completion of Year 5 research by Der Kiureghian (414), OpenSees now includes first-order reliability method (FORM) for reliability analysis, importance sampling (an intelligent Monte Carlo simulation method) for reliability analysis, and a good library of distributions and correlation structures. The project by Law (415) on database support allows more convenient statistical processing of simulations for Monte Carlo approaches, in addition to facilitating data storage and management for post processing and visualization. Progress on these projects responds to concerns raised in the Year 4 site visit report about the need for these capabilities in OpenSees. Further work is planned in Year 6 (414, 413) to provide post-processing capability to do statistical analysis on the output data.

2.1.5.5 Future Plans

Support and continued development for OpenSees will continue given the central role it plays as an enabling technology in PEER. Applications of OpenSees to the testbed and other projects has helped to demonstrate the versatility of the open framework but has also identified the needs for improved modeling features. In Year 6, projects are continuing to complete the implementation and validation of the current structural and geotechnical models and the reliability features. Beyond Year 6, we envision the simulation tool effort to include more emphasis on advanced models for improved performance evaluation including: (1) more complete and robust sensitivity tools necessary for reliability computation, system identification, and design optimization for degrading systems, (2) performance models that automate probabilistic loss modeling features, (3) mixed-field problems such as soil-structure interaction (displacement-pore pressure) and large-displacement problems to improve the efficiency of advanced modeling of SSFI and simulation near collapse. For Year 6 we are also planning projects to apply the computational reliability methods in OpenSees to one of the bridge and one of the building testbeds. This will serve to both validate the sensitivity/reliability tools and focus greater attention toward identifying and propagating important sources of uncertainties in the PEER framework equation.

User support and documentation will be increased in Year 6 by appointing a research engineer specifically tasked with developing an online documentation, providing examples, including validation data, direct user support, and taking the lead in workshops and seminars on OpenSees. We see this as an essential function to build upon the solid user base for OpenSees.

The simulation database will be extended to include performance data and become a web-based service, and a new project will be initiated with computer scientists at the San Diego Supercomputer Center to develop new visualization paradigms and tools for evaluating performance. Development of visualizations of structural response, performance measures, and even loss measures, will greatly improve our ability to understand and control building performance.

In Year 6, initiatives to develop structural and nonstructural performance databases will continue for buildings and bridges. The database design and development will involve defining the meta-data required to represent the component, test environment, loading, sensor data, and processed data. Graphical and numerical data will be stored in a relational database with a web-based interface to the search engine. Linkages will be established between the performance databases and OpenSees, including archiving computed results simulation databases. The goal is to provide engineers the capability to search for experimental data relevant for a structure, use the data to calibrate a simulation model in OpenSees using system identification functions, perform a simulation, process the simulation data in a database, and compare simulated performance with the damage observed in the original experiments of the prototype components.

The structural performance databases in PEER will support the NEES goal of a curated data repository. PEER researchers will work with the NEES system integrator and NEES consortium development team in defining data and meta-data standards for national experimental and simulation databases.

2.1.6 Thrust Area 5 - Structural and Nonstructural Performance

2.1.6.1 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 and systems (including uncertainty and randomness) needed to develop and assess computational tools for simulating performance of buildings and bridges. Performance characterization includes conventional representations such as strength and deformation capacity, but also includes damage parameters such as concrete spalling and its relation to required repair. 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 of 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 elsewhere within PEER to characterize performance.

Activities in Thrust Area 5 have been carefully integrated with projects in other areas. As illustrated in Figure 2.3, primary interaction is with researchers in Task Area 4 to develop and validate models, which improve the fidelity and resolution with which structural performance can be predicted. Component level tests performed in prior years are now being extended to include tests and analyses of more complex systems subjected to dynamic loading in a joint effort with Thrust Area 4 to assess the capabilities and reliability of simulation models in the OpenSees platform. Projects in Thrust Area 5 are also providing performance data to relate *EDPs* to *DMs* of structural and nonstructural components, in a manner consistent with the overall PBEE evaluation and design methodology being developed in Thrust Area 3 and the performance criteria and loss measures being developed in Thrust Area 1. These data feed into the integrative bridge and building testbeds, being coordinated in Thrust Area 3, and knowledge gaps identified in the testbeds related to structural and nonstructural performance will shape future projects in Thrust Area 5. With significant progress having been made on assessing conventionally designed structures, emerging emphasis in future years will be the development of structural systems to enhance performance.

2.1.6.2 TA 5 Strategic Plan

The research plan for Thrust Area 5 is shown in Fig. 2.15, which highlights the following key deliverables: (1) a structural performance library to define and evaluate limit states of performance for components, sub-assemblages, and systems of bridges and buildings; (2) tools (data and models) to quantify structural performance states; (3) tools (data and models) for response or damage assessment of non-structural components of structures; and (4) development of structural components and systems with enhanced performance. This last goal is a change from prior years, and reflects new thinking among the PEER leadership that PEER research should contribute to advances in innovative construction technologies aimed at enhanced performance.

The Thrust Area deliverables relate to both structural and nonstructural components and systems. These include: (1) data on performance of "nonductile" concrete building construction and more modern concrete bridge structural components, organized within accessible databases, and (2) data on performance of broad categories of nonstructural components, including contents, mechanical equipment and systems, and connected nonstructural components such as suspended elements and partitions, organized within accessible databases.

Much of the research during Years 1 through 4 focused 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. Reinforced concrete building components considered relate to columns, column splices and column-to-footing connections, beam-to-column connections, flat-plate-to-column connections, and pile-to-pile-cap connections. For bridges, a variety of tests have been carried out using similar modern, spirally reinforced column specimens to assess effects of loading history, loading rate, and variation of axial load. During Year 5, data from the building and bridge component studies have been analyzed and compiled in projects 526 and 528 (Lehman and Eberhard). A consistent set of damage measures has been developed, and working in conjunction with project 411 (Thrust Area 4), extendable databases to manage and archive this

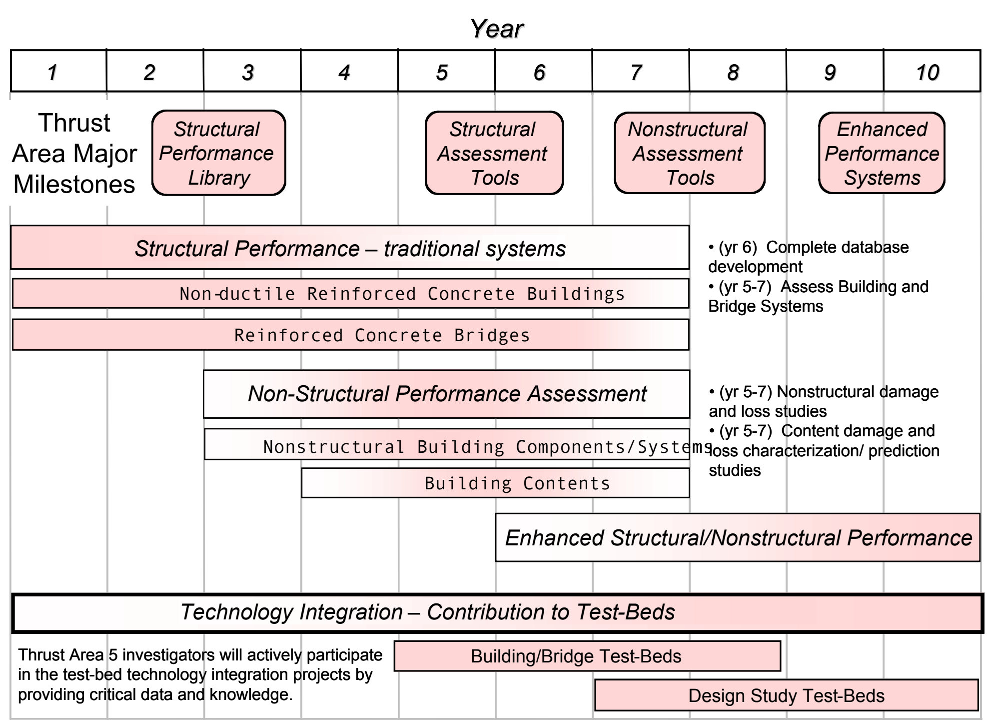

Fig. 2.15 Strategic Plan – Structural and Nonstructural Performance

information are now under development. In Year 4, earthquake simulator (shake table) studies of multiple building-column and single bridge column specimens have been performed to evaluate response and for development/validation of OpenSees models. These are being followed up in Year 5 and 6 with more extensive shake-table validation tests of reinforced concrete building and bridge systems (Moehle and Mahin, 525 and 527).

Based on scoping studies conducted in Year 4, three projects were initiated in Year 5 to characterize the behavior of nonstructural components and building contents. One project focus (524) is architectural and mechanical/electrical components, with the objective to identify and develop a taxonomy to characterize standard building components, develop functional and economic loss models for these elements, and evaluate overall system performance dependency on the nonstructural components. Two other projects (529, 530) are investigating the performance of laboratory building contents through shake table tests of laboratory equipment. Plans for these projects were an outcome of the UC Life Sciences (120) loss project, which showed the major impact of potential losses due to damage of laboratory equipment and contents. These laboratory equipment projects complement on-going lifelines projects to characterize the performance of electric substation equipment and facilities (LL 402, 403, 404, 405, 504, and 703).

2.1.6.3 TA 5 Critical Mass and Level of Effort

The research team for Thrust Area 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 damage evaluation studies. Several have considerable previous experience with the type of component and system being investigated, so that the work being undertaken by PEER benefits substantially by leveraging this prior knowledge. The work being undertaken 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 from these tests.

2.1.6.4 TA 5 Research Advances and Deliverables

The research advances and deliverables in Thrust Area 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 improved simulation/performance models.

- *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.
- *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 PG&E, these tests have resulted in design changes and repair strategies for electrical equipment. Fragility data from these tests are envisioned as being incorporated in future studies on electric system performance under earthquakes.

In keeping with the objective of Thrust Area 5 to develop the knowledge base required to implement enabling technologies, such as OpenSees and Structural and Nonstructural Simulation and Performance Models, much of the work being accomplished is being directly utilized by other investigators, notably those in Thrust Areas 3 and 4. Many of the research accomplishments have also had direct impacts on engineering practice and development of provisions for seismic assessment and design.

2.1.6.5 TA 5 Future Plans

Year 6 plans for the structural performance investigations are largely a continuation of projects begun in Year 5, whose focus is towards synthesizing performance data in on-line libraries (528, 411, 416) and conducting earthquake simulator tests on indeterminate structural building and bridge systems (525, 527). The simulator tests will provide critically needed data to improve our knowledge and validate OpenSees models for complex systems with multiple modes of failure/deterioration. This effort will help integrate earlier year work on footing, splices, beam to column joints, and so on. Beginning in Year 6 and continuing into subsequent years, we are planning new initiatives to investigate structural systems for enhanced performance. Examples of such systems might include self-centering bridge pier and building framing systems that employ post-tensioning systems and controlled yielding of mild reinforcement. Others may involve combined experimental and computational systems where foundation rocking is permitted, or design of retrofit systems for seismically deficient building frames. We anticipate funding one project on enhanced performance systems in Year 6, and two or three projects in future years. These projects will be developed to contribute to projects in Thrust Area 3 to develop methodologies for performance-based design (as opposed to assessment) and development of advanced simulation models in Thrust Area 4.

Work on nonstructural components and contents will proceed with a second year continuation of projects involving simulator tests of laboratory contents (529, 530) and performance of nonstructural building systems (524). In addition, we are planning to fund a new testing project to develop data and damage/cost models for nonstructural partition walls. Partition walls have been identified as a significant source of dollar losses in earthquakes and were among the top priorities identified in workshops on nonstructural components and loss modeling. Aside from generating data that will have significant intrinsic value, this project is envisioned as setting the standard for conducting and documenting tests that can feed directly into the PEER PBEE methodology with probabilistic models to relate EDP-DM-DV.

2.2 Response to Year 4 Renewal Review

The Year 4 Site Visit Team identified several areas where the PEER research program might be improved. These are grouped into nine categories below. Many of these have already been discussed in the thrust area presentations. Furthermore, detailed responses were provided to NSF during a special review panel meeting in July 2001. Therefore, responses are intentionally brief here. In the following text, the expressed concern is in *italics* followed by our brief response.

2.3.1 Uncertainties - *Lack of detailed plans and priority to identify important sources of uncertainty and model the uncertainty within the PBEE framework is currently a weakness but will soon become a threat if not addressed.*

Categorization and modeling of uncertainty is a central aspect in the PEER PBEE methodology, we recognize this as a critical component of PEER's research program, and concur with the review comment that this aspect needs to remain a top priority for PEER. The PEER PBEE framework disaggregates the performance assessment into four distinct parameters (IM, EDP, DM and DV), which isolate and highlight the sources of uncertainty. The number and type of variables affecting the final performance outcome (a probabilistic categorization of key Decision Variables, DV) is tremendous, beginning with uncertainties in seismological data on earthquake hazards and continuing through to uncertainties in relating damage to repair costs, downtime, etc. We have and will continue to focus PEER's resources on characterizing (identify, quantify, and propagate) the most important sources of uncertainty, in terms of their significance on affecting the Decision Variables.

Through continued development of the PBEE methodology we are striving to identify all significant sources of uncertainty. Those parameters whose uncertainty is deemed to be significant are being pursued further by (1) seeking to quantify the sensitivity of the performance outcome to the parameter and to the degree we can (2) quantify the variability in the parameter. While we will strive to quantify important parameters, we realize that there will be topics that are important but beyond PEER's scope or resources (e.g., this may include some of the many varieties of nonstructural components, and some of the economic considerations affecting the decision variables). In such cases, we will carefully document assumptions that we need to make in lieu of having definitive data to fully describe the uncertainty. In this respect, a virtue of the PEER PBEE methodology is that it helps break the total uncertainty down into quantifiable parts that can be dealt with on a case-by-case basis that can chart a road map for continued research and development.

In Year 5 PEER has initiated projects that specifically address uncertainty issues, including the following projects listed in Table 2: 328 (probabilistic vector-valued ground motions), 228 (geotechnical uncertainties), 317 (propagation of uncertainties), 318 (bridge fragility), 118 and 122 (building loss assessment), and 413 and 414 (computational reliability). Moreover, the testbed studies that we have embarked on in Year 5 are an important mechanism for helping to identify and propagate important sources of uncertainty. Projects in Thrust Area 1 are also addressing the question of how to effectively communicate uncertainties to key stakeholders for decision-making about performance objectives.

2.3.2 OpenSees - *Lack of documentation, validation, and a timetable for the development of OpenSees. Inconsistent perceptions/visions of OpenSees by different researchers. Inadequate support for information technology, computer science, and computer visualization for the* *development of OpenSees. Lack of stochastic simulation modules in OpenSees for Monte Carlo simulation.*

Considerable progress has been made to address most of these concerns over the past year. Features available in OpenSees have been improving, as has the on-line documentation and usage by researchers both within and outside PEER. As noted previously under Thrust Area 4 accomplishments, several user/developer workshops and other information sessions have been held, and future sessions are planned. Through the testbed exercise, OpenSees is being used by more PEER researchers on larger, more-realistic problems. With regard to stochastic simulation modules, two dedicated projects (413 and 414) were initiated in Year 5 to develop and implement FORM/SORM techniques in OpenSees, and several researchers are using OpenSees to run Monte Carlo type simulations. With regard to the computer science, information technology, and visualization support, PEER is making efforts to involve researchers with background in these areas and to leverage alternative funding sources targeted to the high-performance computing aspects of OpenSees. Further details on this are reported above in the Thrust Area 4 report in Section 2.2.5.

2.3.3 Transportation - *Bridge performance research seems less well integrated into the PBEE framework than building performance. Transportation research is not well integrated with other research activities*

During Year 5, the research program has been organized and coordinated around the testbeds, which has proved to be an effective mechanism at integrating the bridge and highway network research into the global PEER PBEE framework. Several meetings have been held for the bridge and highway testbeds (Nov. 2001, Jan. 2002, May 2002), which brought together PEER researchers, Caltrans engineers, and other professionals from all relevant disciplines (site response, ground deformations, pile foundations, bridge piers and superstructure, highway fragility modeling transportation modeling, and economic impact). Simulations studies of the Humboldt Bay and I-880 bridge testbeds are progressing well with active involvement of geotechnical and structural engineering researchers. Discussions on bridge fragility functions and decision variables have provided a natural linkage between the transportation (highway network) and bridge engineering researchers. Over the past two years, Caltrans has developed greater interest in the seismic risk analysis of the Bay Area highway network and been a catalyst to promote collaboration between the PEER highway modeling effort and one by the MCEER-FHWA group. Finally, in Year 5, supervision and coordination of the transportation simulation projects (321, and 322) was moved from Thrust Area 1 to Thrust Area 3, so as to provide closer integration with the PBEE methodology development effort.

2.3.4 Social Sciences - *PEER still has insufficiently integrated the social sciences into both its research and education programs and its Student Leadership Council. PEER lacks needed expertise from social sciences and mathematics in the area of complex adaptive systems.*

Societal considerations are central to PEER research concerning loss estimation and decision-making and to the testbeds. As discussed previously in the Thrust Area 1 strategic plan (Section 2.2.2), we initiated several projects were in Year 5 and planned for Year 6 to address loss estimation, decision-making, and public policy. Public policy and societal considerations were a central part of this year's PEER's Scholars Course (weekend seminar in public policy led by Peter May at University of Washington). Consideration of complex adaptive systems is an important consideration of several projects, most notably the work by the Batelle group in studying decision-making for lifeline organizations including involvement of decision theorists and decision modelers.

Finally, as explained in PEER's written response to the Year 4 site visit (dated July 2001), we remained unconvinced that development of mathematical models of the decision-making process would be optimal use of PEER funds and effort relative to our other priorities. Moreover, our Business and Industry Partners and Scientific Advisory Committee have not been encouraging of diverting resources to this endeavor. Rather, these groups have emphasized that PEER should emphasize validation (reliability and accuracy of the PBEE methodology/technologies) and should provide a flexible framework that can be applied and interpreted by engineering professionals and decision makers in different ways. PEER leadership, including the Director, have reviewed salient work in the area of complex adaptive systems; appropriate applications within PEER will be weighed in relation to other needs in the research program in the years ahead.

2.3.5 - Business and Industry - *Underutilization of professional expertise in the Business and Industry Partnership (BIP) for strategic planning, project selection, and involvement in the research projects. Low involvement of undergraduate students in the research projects. Lack of continuing education for practitioners, building officials, etc.*

Insofar as the research program is considered, the Year 5 emphasis on the methodology testbeds has provided a good vehicle for involving Business and Industry Partners more directly in the research. The testbeds all involve real facilities, which provide opportunities for the business partners to lend practical advice on modeling and assessment and to contrast the merits of the PEER PBEE methodology with the current state of practice. Other mechanisms for greater communication and involvement of practitioners and undergraduate students are reported in Chapters 3 and 4 of this report.

2.3.6 Deliverables - *Concern of business and industry that useful deliverables have yet to be developed by the PEER core program, e.g., the Scientific Advisory Committee (SAC) and BIP SWOT analyses both indicate concern over the lack of deliverables to date.*

In part, the concern over lack of useful deliverables is being addressed by the natural maturing of projects during Year 5, evident from the increasing number of PEER project reports and papers. Aside from this, a number of concerted efforts have been made to disseminate useful PEER products to practitioners. The format of the PEER Annual Meeting held this past January (2002) was purposely structured with parallel sessions to provide the opportunity for more detailed presentations of PEER project results to practitioners. Written material from the annual meeting was prepared and distributed in the form of "Research Digests" that provided concise summaries of practical outcomes from the PEER projects.

2.3.7 Planning - *Insufficient detail and planning for years 5-9.*

As the PEER research program matures, increasing emphasis is being placed on research synthesis with projects at the *Enabling Technologies* and *Technology Integration* levels of our Systems Level Strategic Plan (Fig. 2.1). This revised emphasis and the project definitions/awards represent the conscious decision on the part of the PEER Research Executive Committee. The methodology testbeds introduced in Year 5 have been another valuable tool for identifying critical unmet needs and gaps in the research. These needs and priorities are reflected in the overall and thrust area specific research plans described in this report. The ongoing strategic planning process in PEER results in very detailed outlines of research needs and plans; the informal format of these documents facilitates continual development and growth, but is not conducive to presentation in formal reports.

2.3.8 Hazard Characterization - *Lack of development and use of uniform characterization of the earthquake hazard by all thrust areas.*

Questions on how to characterize seismic hazard within the context of the PEER PBEE methodology are still under active debate. This is due to several reasons, ranging from how one quantifies the "damaging feature" of a ground motion to the extent to which local site effects are explicitly modeled in the performance analysis of a facility. Therefore, some differences of approaches are expected to exist in various PEER projects – particularly a few projects, which are specifically charged with looking into this topic (224,228, 317, and 328). To help resolve the significant issues and develop a more consistent approach, during the past year we have had three small meetings/workshops to address the question of hazard characterization (Jan., April, and May 2002). While some important unresolved issues remain, we are taking efforts to educate PEER researchers and industry about what we feel is the best strategy for hazard characterization. To help achieve uniformity in the testbed studies, we established a short-term project (#232) to develop a consistent hazard curve characterization and suites of ground motions for each testbed.

2.3.9 Database Management - *Unclear plans for development of database management for PBEE and decision-making data.*

Our Year 5 research and plan for Year 6 includes several projects in Thrust Areas 2, 4, and 5 to address the important need for database management tools and databases themselves with information on building and bridge performance. This includes, for example, project 2LO2 on a geotechnical database, project 415 on a simulation database, projects 411, 416, and 528 on structural performance databases, and project 524 on a database for nonstructural components. These are in addition to the ground motion database completed in Year 3. We envision these databases to have several uses both to facilitate PEER's research program itself and to contribute to the enabling technologies for PBEE.

In terms of database architecture, our vision is to have a fairly generic database design (schema) that can accommodate experimental and simulation data and assist in comparison, validation, etc. One concept we are pursuing is to represent experimental data in a common format as simulation model data in OpenSees, so as to facilitate utilization of the experimental data for both model validation and interpretation of simulation results. We do see an opportunity for our database development efforts to feed into the larger collaboratory and curated database development efforts within the NEES program.