2. STRATEGIC RESEARCH PLAN

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

2.1 PEER Strategic Research Plan

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

The PEER research program for developing performance-based earthquake engineering is guided by a strategic research plan and organized around four thrust areas. The strategic plan has evolved over the life of the center, including a significant restructuring of the thrust areas in Year 7 (see Section 2.2), as the research matures. The strategic plan is illustrated by a series of graphics that display the integration of various disciplines, projects, and products, and ensure balance among research aimed at producing fundamental knowledge, enabling technologies, and systems-level methodology development and implementation. An overview of the systems-level research plan is described in this section, followed by details on specific milestones, research organization, and thrust-area specific plans in subsequent sections.

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

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

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

- One level of decision is that of designers, owners, or investors in individual facilities (e.g., 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

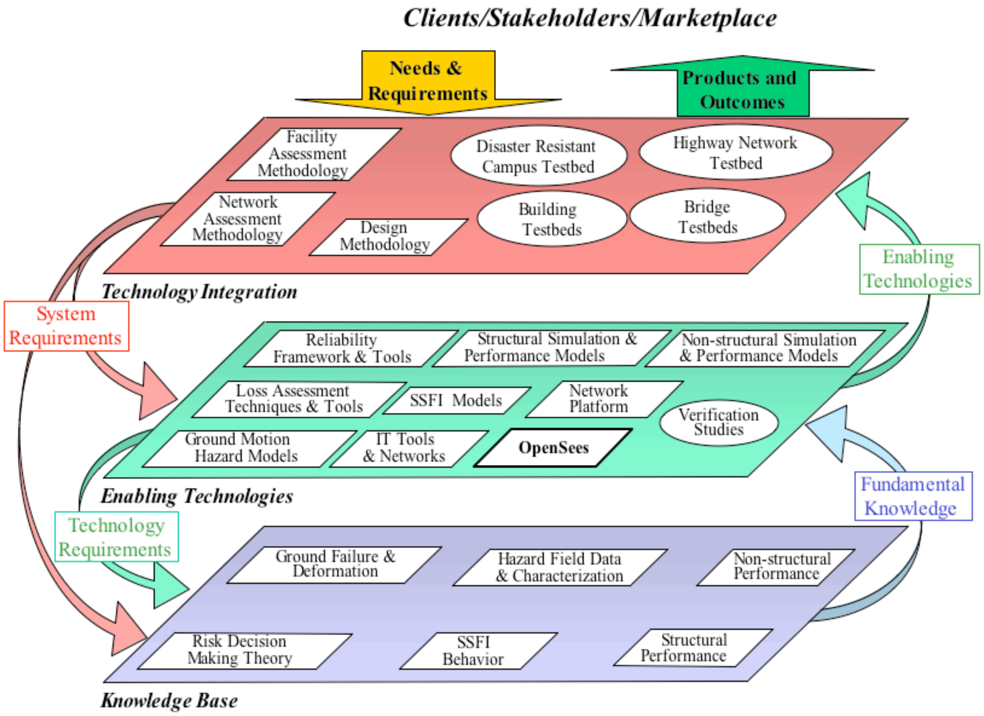

Figure 2.1 - Systems Level Strategic Plan

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, or for a scenario event. This differs from the current approach for seismic design or assessment of individual facilities, which aims to meet specified component criteria for loadings 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.

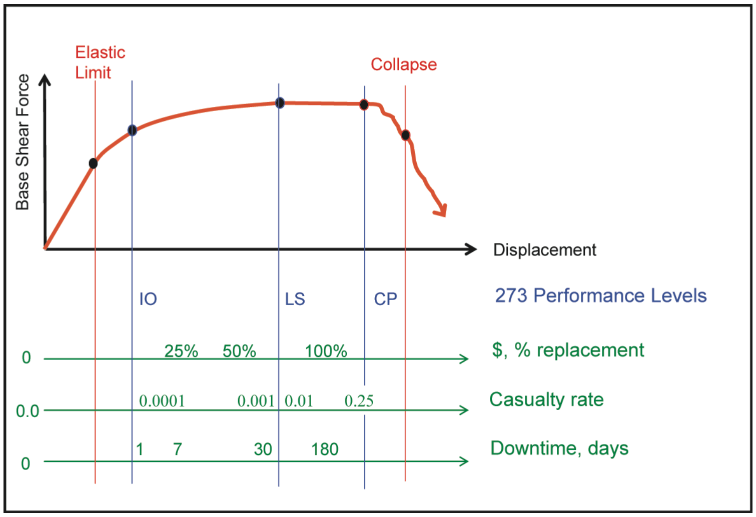

Figure 2.2 – Idealized relation between performance and load-deformation response (after Holmes, PEER 2001 Annual Meeting)

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

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

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

2.1.2 Technology Integration Plane

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

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

2.1.2.1 Methodology Description

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

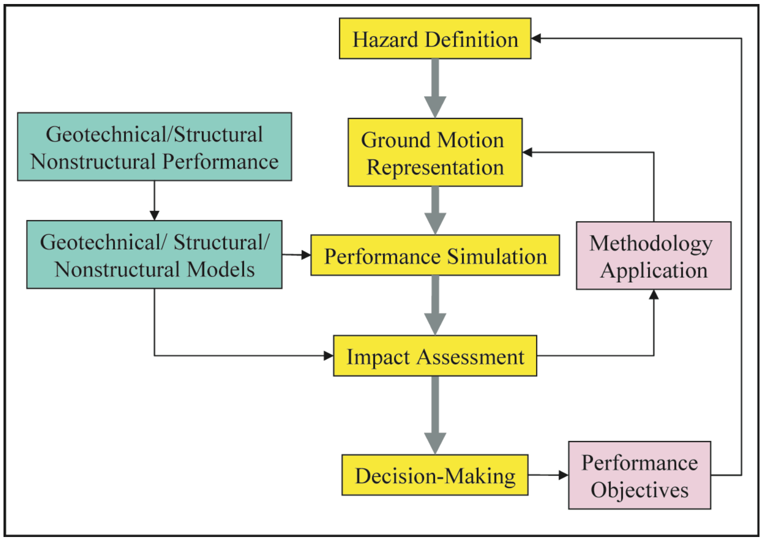

Figure 2.3 – Research elements in the performance-based earthquake engineering methodology.

- *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 inelastic strains, which are then related to component damage measures.
- *Impact Assessment* – Ideally the impact is in terms of the three performance measures adopted in this program, namely, direct dollar loss, functional loss, and casualty loss.

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

2.1.2.2 Formalization of the Methodology.

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

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

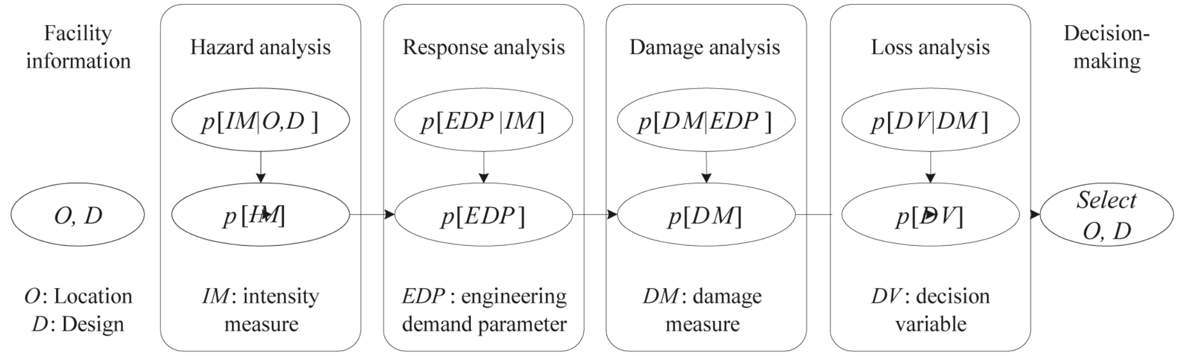

Figure 2.4 – Underlying probabilistic framework of PEER's performance-based earthquake engineering framework

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

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

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

The methodology framework just described and shown in Figure 2.4 is an effective integrating construct for both the PBEE methodology itself and the PEER research program. The framework provides researchers with a clear illustration of where their discipline-specific contribution fits into the broader scheme of PBEE. Moreover, the framework 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.

2.1.2.3 Proof-of-Concept Testbeds.

During Years 5 to 7, PEER embarked on a series of proof-of-concept testbeds as identified within ovals in the *Technology Integration Plane* of Figure 2.1. These testbeds had the multiple objectives to: focus and integrate the multidisciplinary research; test research products and identify needed research; and provide a mechanism for PEER researchers and Business and Industry Partners to work jointly on research.

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

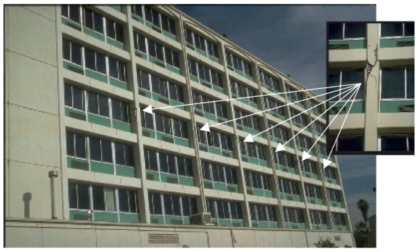

Figure 2.5 – Van Nuys building

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

Figure 2.6 – Examples of equipment in UC Science Building

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

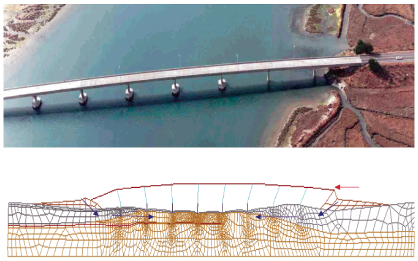

Figure 2.7 – Humboldt Bay Bridge

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

Figure 2.8 – I-880 Bridge

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

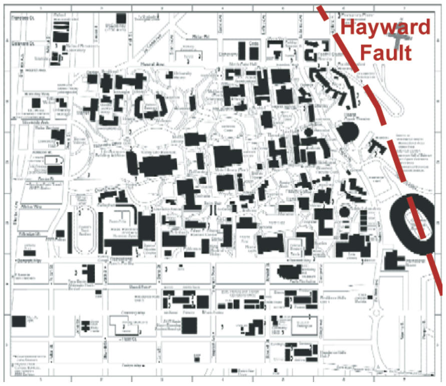

Figure 2.9 – UC Berkeley Campus

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

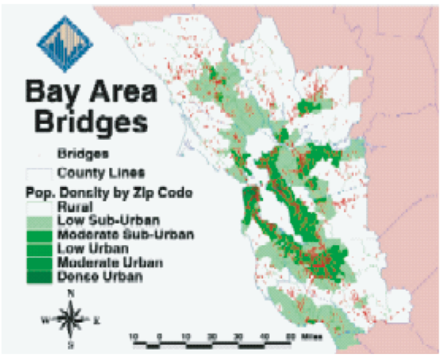

Figure 2.10 – Highway Network

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.

Specific efforts on each of these testbeds as just described have served an important role to help integrate the PEER research in Years 5 through 7. Details on the coordination and progress are available on-line at http://www.peertestbeds.net. These testbeds have been a major focus during the past two years and culminated with summary presentations at PEER's Annual Meeting in Year 7. As described later, the success of the testbeds to integrate and focus the research has motivated a restructuring of PEER's research management for Years 8 to 10 to include more emphasis on integrating the methodology and enabling technology products for building system performance, bridge system performance, and a new tri-center initiative on the performance of geographically distributed transportation and electric utility systems.

2.1.3 Enabling Technologies Plane

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

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

  PEER researchers have begun to develop simulation methods for use in NSF’s George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program; and during this past year, the System Integrator for NEESgrid (http://www.neesgrid.org/index.php) has adopted *OpenSees* as a standardized simulation platform for NEES. The open architecture of *OpenSees* provides support for combining computational simulation with advanced experimental methods, such as the pseudo-dynamic and hybrid testing methods. In addition, *OpenSees* supports parallel processing, which will become increasingly important for solving large problems on the NEES grid.

  OpenSees plays an important role in education because students are more motivated to learn about computer science and advanced applications once exposed to the modern computing and software approaches incorporated in *OpenSees*. The software is “open source,” meaning that all parts of the code are available for users to see, check, track changes, and contribute to. The *OpenSees* website (*opensees.berkeley.edu)* is being continually maintained and enhanced to provide up-to-date downloads, source-code tracking, and communication. This is the first instance of an open-source, community software in earthquake engineering. Currently, more than 300 users have registered with the *OpenSees* software repository, including many who have attended hands-on workshops run by PEER.

  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. The simulation and validation activities for the testbed projects include:

  - *Component Simulations* – The analytical models developed within the *Enabling Technologies Plane* (Figure 2.1) were derived mainly from physical experiments on components. These physical tests serve as one form of testbeds for *OpenSees*.
  - *System Simulations* – Recorded earthquake response data for the Van Nuys testbed building and Humboldt Bay Bridge have provided an excellent opportunity to implement and refine *OpenSees*. Additional system simulations include shake table tests conducted by PEER and collaboration with other centers (e.g., collaboration with NCREE in Taiwan has included validation studies based on a pseudo-dynamic test of a full-scale three-story frame).
  - *Performance Databases* – System simulations generate a large amount of data, and the data must be statistically processed for determining performance characteristics. The testbeds provide an ideal opportunity to utilize the databases, and the connections between *OpenSees* and the databases, for performance evaluation.

- *Network Platform* – Through PEER's Highway Demonstration Project, a suite of analysis and GIS database software has been assembled for simulating the seismic performance of highway networks. The platform is set up for the San Francisco Bay Area highway network, and incorporates detailed data describing geographically distributed seismic hazards, bridge descriptions, and transportation links. This platform is unique from other geographically distributed loss analysis systems in that it links transportation network analysis software with data on damaged bridges obtained from a comprehensive seismic risk analysis. Beginning in Year 6, development of the Network Platform has been incorporated under a new EERC Tri-Center Initiative on Geographically Distributed Lifeline Systems. As outlined in Volume III of this report, the tri-center initiative is focused primarily on highway and electric utility lifeline systems. In addition to the core programs of the three EERCs (PEER, MAE, and MCEER), the initiative involves the PEER-Lifelines Program, the MCEER-FHWA program, and externally funded Caltrans research. As part of the tri-center collaboration, PEER has agreed to orient its bridge performance and highway risk analysis efforts to be compatible with a seismic risk assessment program, called REDARS, whose core development is supported by MCEER-FHWA. With regard to the Network Platform, PEER envisions that its research focus will be to develop improved modular components of REDARS and to use REDARS in studies of system performance. PEER's specific research contributions will include development of improved models for evaluating bridge performance, hazards due to ground shaking and ground deformation, and characterization and propagation of uncertainties in the risk assessment methodology. A related longer-term goal of both the tri-center initiative and PEER is to explore ways of extending the highway network models to evaluate electric utility systems. Further details on these activities are summarized in the Volume III report.

- *Other Enabling Technologies* – Other enabling technologies, which appear in Figure 2.1 include:
  - *Hazard Models* – the hazard models represent the seismic hazard in terms of magnitude, mechanism, recurrence; define attenuation of ground motion parameters to the site; and facilitate selection and scaling of representative ground motions, including an online ground-motion database.
  - *Geotechnical Simulation and Performance Models* – the simulation models model the mechanical behavior (e.g., load-deformation response) of various components/media,

while the performance models relate performance to the various stages of mechanical behavior.

- *Structural Simulation and Performance Models* – these are the structural parallels to the *Geotechnical Simulation and Performance Models.*
- *Nonstructural Simulation and Performance Models* – these are the nonstructural parallels to the *Geotechnical Simulation and Performance Models.*
- *SSFI Models* – soil-structure-foundation interaction models are needed to supplement geotechnical and structural models.
- *Reliability Framework and Tools* – these include procedures for selecting modeling parameters, frameworks for assessment methodologies (e.g., Equation 1), and implicit and explicit analytical procedures embedded within *OpenSees* and the Network Platform.
- *Loss Assessment Techniques and Tools* – these provide linkages between physical performance measures such as damage and the economic or other social impacts, for use in both *OpenSees* and the Network Platform.
- *IT Tools* – these include (a) the development and use of visualization tools to improve ways of expressing performance, and (b) networks and databases to facilitate computation and sharing of information.

2.1.4 Knowledge Base Plane

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

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

The Needs and Requirements described in Section 2.1.1 define in a broad sense the ultimate goals of the PEER research program; and descriptions of the *Integration, Enabling Technologies*, and *Knowledge Base* planes in Sections 2.1.2 through 2.1.4 highlight significant research focus areas and products. This section, together with subsequent sections of this chapter, provides further details of the research program organization and specific milestones as related to the needs for implementing PBEE. Section 2.2.1 begins with a brief overview of the research organization, followed with a description of thrust area research coordination and milestones (Section 2.2.2) and a list of Year 7 and 8 research projects (Section 2.2.3 and Table 2).

2.2.1 Research Organization

PEER carries out research within two administratively distinct but coordinated programs. The *Core Research Program* is that portion of the program supported by the core NSF funds and matching funds. That program has the objective of developing the overall methodology for PBEE, in addition to key enabling technologies (e.g., *OpenSees* simulation models) and decision making criteria. 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. Research conducted through the two programs is coordinated through center-wide strategic planning.

During Years 2-7, PEER's research program was organized through five thrust areas, which were defined around the PBEE methodology components as illustrated by the flowchart of Figure 2.11. As listed in Figure 2.11, these thrust areas dealt with: (1) loss models and their relationship to stakeholder decision making, (2) earthquake ground shaking and ground deformations and the transmission of these effects into the structure through foundations, (3) development of the overall PBEE assessment and design methodologies, (4) simulation and information technologies, including *OpenSees* and on-line databases, and (5) performance of structural and nonstructural components. While this research management structure has been an effective mechanism to formulate the PBEE methodology and its underlying components and technologies, as the research has matured, the PEER Research Committee felt that a reorganization of the thrust areas would strengthen the research.

During Years 5-7, the proof-of-concept testbeds (described previously in Section 2.1.2.3) served an important role to synthesize the methodology components; and, in many respects provided a natural framework to manage the research. In particular, the testbeds proved to be an effective means to focus the research to address specific needs of the PBEE applications to buildings and bridges and the networks of which they are a part. While the PBEE methodology and components, as shown in Figure 2.11, are generic in concept, the testbed exercises demonstrated that important aspects of the PBEE implementation to bridge and building systems are quite unique. For example, whereas the three categories of decision variables (dollar losses, functionality, and casualties) are general, the relative importance of each is quite different for buildings and bridges. For buildings, all three metrics tend to have equal importance (though differences exist between various stakeholder groups). On the other hand, for bridges post-earthquake functionality tends to be the metric of overriding importance, particularly with respect to how the bridge performance impacts the transportation network. These differences in emphasis lead to differences in how the PBEE methodology and tools are applied to bridges

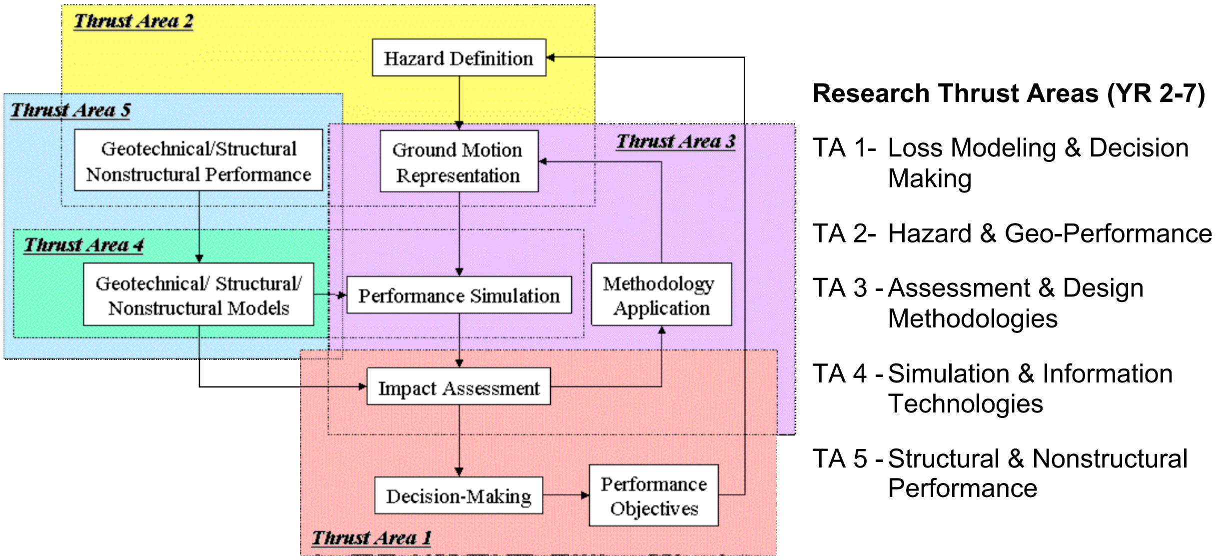

Figure 2.11 – Research thrust areas (Years 2 – 7)

versus buildings. Further distinctions between bridges and buildings extend to other areas of the methodology, beginning with basic modeling attributes for the system simulations.

After thoughtful deliberation and consultation with the PEER Scientific Advisory Committee, the PEER Research Committee decided, in Year 7, to reorganize the research management around the four thrust areas shown in Figure 2.12. Aside from the reduction from five to four thrust areas, the reorganization reflects an emphasis on the two major application areas to: TA I *Building Systems* and TA II *Bridge and Transportation Systems*. As described in further detail later, these two thrust areas encompass all major aspects of the PBEE methodology and enabling technologies related to these applications. Thrust Area IV on *Simulation and Information Technologies* has much the same emphasis as the previous Thrust Area 4, a key concern of which is the development of the *OpenSees* framework and models. One change within TA IV is a stronger linkage to validation testing and simulation of structural and geotechnical components, which now are planned and managed from within this thrust area. This is in contrast to the previous structure where much of the validation testing occurred in TA 2 (geo-performance) and TA 5 (structural performance). Finally, the new TA III encompasses the *Lifelines Program*, whose primary focus is on characterization of earthquake ground motions and ground deformation and their effects on transportation and electric utility components.

As further illustrated in Figure 2.12, the hazard characterization of TA III and the simulation technologies of TA IV have direct links to the application areas of TA I and TA II. Additionally, TA II and III share close collaboration with the tri-center collaboration on geographically distributed transportation and electric utility systems (see Volume III). Finally, all four thrust areas are encompassed by the common PBEE methodology, which provides a consistent linkage from ground motion *Intensity Measure (IM)* through system demands and damage (*EDP* and *DM*) and on through to the decision variables (*DV*).

2.2.2 Research Needs, Outcomes, and Integrative Milestones

The graphic in Figure 2.13 shows an overview of how various components of the research program are coordinated to respond to the needs for PBEE, which represent the desired outcome of PEER's research. At the top of this figure are eight specific topics, which articulate the

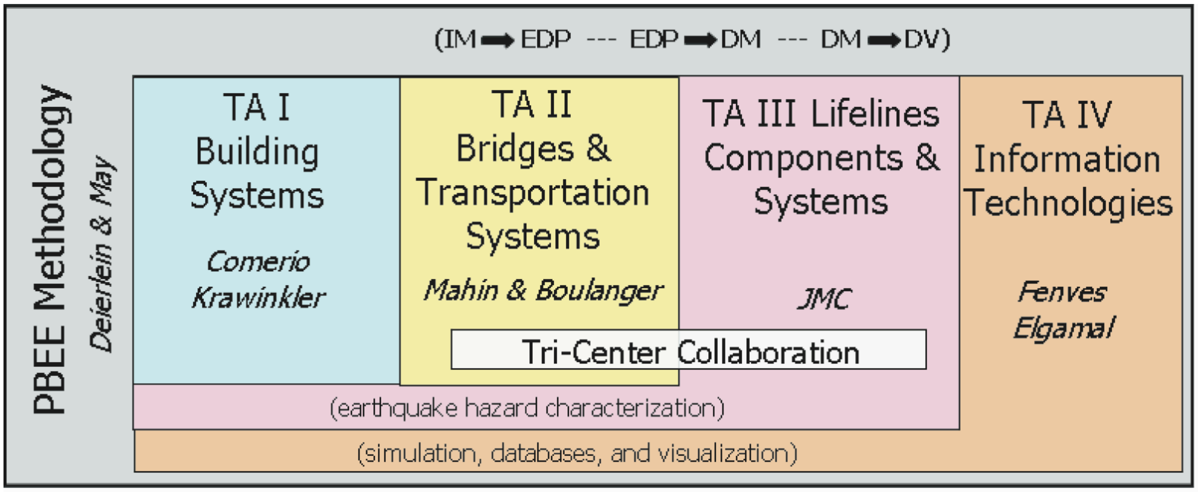

Figure 2.12 – Realignment of research thrust areas (Years 7 – 10)

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

To maintain readability of Figure 2.13, graphical links connecting the topical research areas to *Integrative Milestones* to the *PBEE Needs* are not shown. However, linkages are considered in PEER's strategic planning and are evident in the detailed thrust area strategic plans discussed later in this chapter. Further details on the *PBEE Needs*, *Integration Milestones*, and *Demonstration Milestones* are given in the following subsections.

2.2.2.1 Research Needs and Outcomes

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

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

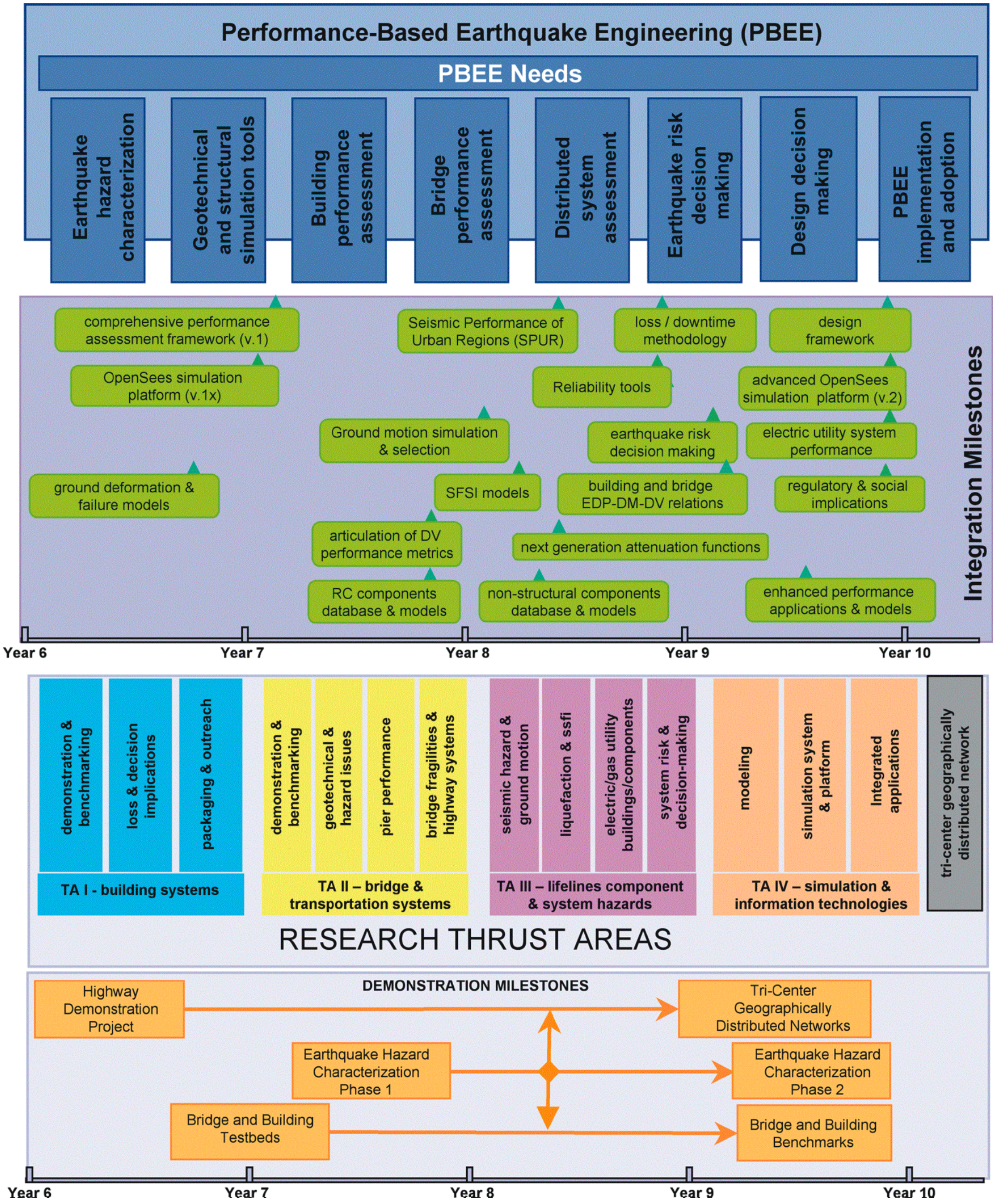

Figure 2.13 – Outcomes, Integrative Milestones, and Thrust Areas

- *Design Decision Making:* Methodologies and modeling simplifications to apply PBEE assessment techniques to make design decisions for new buildings and bridges. Emphasis is on guidelines on evaluating tradeoffs in performance objectives by altering of engineering demand parameters, which relate to key decision variables.
- *PBEE Implementation and Adoption:* Background information, guidelines, and strategies to facilitate implementation of PBEE techniques in practice and building codes and standards.

2.2.2.2 Integrative Milestones

The *Integrative Milestones* shown in Figure 2.13 are significant outcomes resulting from the efforts of researchers in one or more thrust areas. The tick marks associated with each milestone indicate approximately the point in time (measured with respect to the horizontal axis) when the research is to the point that an identifiable product has been achieved. As implied by the term milestone, these achievements are not viewed as final end products, but rather as points in an ongoing development where we can claim a certain degree of consensus on approaches and techniques for PBEE. Highlights of each milestone are as follows:

- *Comprehensive performance assessment framework* – detailed specification of all major steps in determining input data, conducting simulations, and processing uncertainties for comprehensive performance assessment of individual facilities, employing the IM-EDP-DM-DV path.
- *Loss/downtime methodology* – methodology for probabilistic assessment of direct dollar losses and facility downtime, intended to improve upon due-diligence evaluations (e.g., Probable Maximum Loss, PML) of facilities for better informed risk management decisions by owners and financial/insurance institutions.
- *Design framework* – methodology, criteria and guidelines for performance based design of new and existing structures. Emphasis will be on ways to alter and target desired performance objectives by design parameters for the foundation, structural and nonstructural components, and contents.
- *Earthquake risk decision making* – guidelines and examples for utilizing seismic performance metrics to make risk management decisions, based on multiple considerations including benefit-cost, investment trade-offs, business interruption planning, etc.
- *Regulatory and societal implications* – evaluation and benchmarking of present building code regulations and other societal factors related to the adoption and acceptance of performance-based building codes. Included will be critiques of PBEE relative to current design practice, considering observations from testbed and benchmark studies.
- *Building and bridge EDP-DM-DV relations* – data and models to relate engineering parameters to damage and quantifiable decision variables for buildings and bridges. For buildings, emphasis will be on collapse and losses associated with damage to structural and nonstructural components, repair costs, and occupancy interruption. For bridges, the major decision variables relate to traffic closure and restoration times.

- *Articulation of DV performance metrics* – consensus on key decision variables and preferred ways of articulating these decision variables for different stakeholders.
- *OpenSees simulation platform (v1, v2)* – version updates of *OpenSees* with new modeling and computational capabilities. The final version 2 will have advanced network-enabled computational, database, and visualization features.
- *Seismic Performance of Urban Regions (SPUR)* - demonstration of integrated simulation and visualization platform for earthquake ground motions and their effects on urban infrastructure facilities. Section 2.6 provides further details of this collaborative project, which utilizes earthquake hazard and simulation research from Thrust Areas III and IV.
- *Reliability tools* – toolbox of semi-automated procedures implemented in *OpenSees* to facilitate probabilistic assessment of PBEE parameters IM-EDP-DM-DV.
- *Ground motion simulation and selection* – data, models, and procedures for defining seismic hazard and input ground motions for simulation and performance assessment of buildings, bridges, and other facilities.
- *Ground deformation & failure models* - data, models, and procedures to predict ground deformations as a function of seismic hazard intensity and ground characteristics.
- *Next generation attenuation functions* – culmination of work to incorporate expanded and improved ground motion data into improved attenuation functions for spectral acceleration and other *IMs* as a function of earthquake magnitude and distance from site.
- *Soil Foundation Structure Interaction (SFSI) models* – implementation, validation, and documentation of *OpenSees* simulation models for shallow and deep foundations, with applications to bridges and buildings.
- *RC component database and models* – data and models for simulation of structural response and damage to reinforced concrete components, including beams, columns, joints (column splices, beam-column, slab-column), and walls.
- *Nonstructural component database and models* – data and models to evaluate seismic damage and consequences to nonstructural building components and contents. Organized around a comprehensive taxonomy, data and models will be developed based on published literature and selected tests conducted by PEER.
- *Enhanced performance applications and models* – component models, simulation tools, and benchmark studies to evaluate performance of enhanced reinforced-concrete systems, which through use of new concepts or materials provide cost-effective alternatives to conventional systems.

2.2.2.3 Demonstration Milestones

Referring to the *Demonstration Milestones* at the bottom of Figure 2.13, PEER has emphasized demonstrations of the PBEE methodology in two major areas – (1) individual bridge and building facilities, and (2) transportation networks and other distributed systems. In addition, there is a third milestone related to PEER's efforts (particularly through its *Lifelines Program*) to dramatically improve methods to characterize earthquake ground shaking hazards for PBEE.

The Year 7 demonstration milestone in Buildings and Bridges marked the completion of a two year focus on the four proof-of-concept testbeds, which were described in Section 2.1.2.3.

Beginning in Year 7, the demonstration projects have shifted to generalized studies on performance assessment and benchmarking of modern reinforced concrete buildings and bridges. Like the proof-of-concept testbeds, the benchmarking exercises will serve to integrate and focus the interdisciplinary research and provide a mechanism for packaging the assessment methodologies in a consistent format. Additionally, the change in emphasis from studies of specific testbed facilities to generalized classes of facilities will serve the emerging needs for design and system considerations. The benchmark studies will provide data on the reliability and implied performance of current codes and practice, which was a high priority research need identified in discussions with researchers and industry partners at the 2003 PEER Annual Meeting. In addition to providing a benchmark against which to gage socially acceptable performance targets, these studies will highlight opportunities for improving design procedures, with emphasis on understanding how changes in key design parameters (strength, stiffness and ductility) affect the seismic performance. For bridges, the benchmark studies will lead to improved fragility models, which will be used in highway network studies to help establish appropriate performance targets for bridges.

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

The third demonstration milestone concerns the characterization of earthquake hazards for PBEE. A major component of this milestone is the Next Generation Attenuation project, which is a major initiative of the Lifelines Program (under Thrust Area III) to dramatically improve attenuation models used as the basis for probabilistic seismic hazard analyses. Related efforts in TA I-III are addressing issues associated with the choice of ground motion intensity parameters, ground motion scaling procedures, site effects and soil-structure interaction, as they relate to performance predictions of buildings and bridges. The outcome of the Phase I and Phase II milestones will be validated consensus models for quantifying ground motion hazards and procedures for selection and calibration of ground motion records as input to simulation models of buildings and bridges.

2.2.3 Years 7 and 8 Research Project Summary

Research projects for the current Year 7 and those proposed for Year 8 are summarized according to thrust areas in Table 2 (located at the end of this chapter). Detailed summaries of all current (Year 7) projects are included in Volume II of this report. Each project is identified with a project number, principal investigator (PI), and title. These project identifiers are referenced in the thrust area research summaries in Sections 2.3 through 2.6. Project numbers of the form xyz2003 (or xyz2004) refer to projects that are administered through the Core research program. Note - due to the thrust area reorganization in Year 7, the prefix to the project numbers "xyz" do not necessarily correspond to the current thrust area number designations (e.g., TA I to IV). Projects with other three digit numbers (e.g., 701), or three digits plus one letter (3G02) are those administered through the Lifelines Program.

Funding amounts specified in Table 2 are for the total budgeted amount (direct plus indirect costs). Some of the differences in the budget amounts reflect difference in indirect rates, which are considerably less for projects funded at University of California institutions using California state matching funds. Indirect rates on the California projects are typically on the order of 10%, versus rates of 50% to 60% on projects supported by non-California funds. There are some Year 8 projects for which the project PI and funding allocation are undetermined at this time, pending final accounting of residual funds from Years 6 and 7, and pending funding provisions for the Lifelines Program TA III).

2.2.4 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. Together with another research committee member, Professor Peter J. May (Political Science, Univ. of Washington), Deierlein oversees the integration of the research under the PBEE methodology and its relationship to decision making by key stakeholder groups (see Fig. 2.12). Thrust Area I, *Building Systems*, is led by Professors Mary Comerio (Architecture, U.C. Berkeley) and Helmut Krawinkler (Structural Engineering, Stanford). Thrust Area II, *Bridges and Transportation Systems*, is led by Professors Stephen A. Mahin (Structural Engineering, U.C. Berkeley) and Ross Boulanger (Geotechnical Engineering, U.C. Davis). Professor Boulanger joined the *Research Committee* in Year 7 to augment representation of geotechnical engineering on the committee. Thrust Area III, *Lifelines Component and System Hazards,* is managed by a *Joint Management Committee* of the *Lifelines Program* (see below) and is represented on the PEER *Research Committee* by Jack Moehle, who is the PEER *Director* and professor of Structural Engineering at U.C. Berkeley. Thrust Area IV, *Simulation and Information Technologies*, is led by Professors Gregory L. Fenves (Structural Engineering, U.C. Berkeley) and Ahmed Elgamal (Geotechnical Engineering, UCSD).

The *Lifelines Program* contractual agreements require a close coordination among the researchers and sponsors. To meet those requirements, PEER has established a series of Topic Area Leaders to provide close oversight and coordination of those projects funded through the Lifelines program. These topic leaders provide a natural technology transfer mechanism to industry. Director Moehle works directly with Dr. Yousef Bozorgnia, *Associate Director for Sponsored Projects and Technology Transfer,* to provide overall coordination of the program. Topic Leaders are as follows: *Earthquake Ground Motion*, Dr. Norman Abrahamson (Seismologist, PG&E) and Dr. Brian Chiou (Seismologist, Caltrans); *Site Response*, Dr. Clifford Roblee (Geotechnical Engineering, Caltrans); *Permanent Ground Deformation*, Mr. Thomas Shantz (Geotechnical Engineering, Caltrans); *Electric Substation Equipment Vulnerability,* Mr.

Eric Fujisaki (Structural Engineering., PG&E); *Electric System Building Vulnerability,* Mr. Kent Ferre (Structural Engineering, PG&E); *Network System Seismic Risk*, Dr. Stuart Nishenko (Seismology, PG&E). These topics are coordinated through the associated thrust areas.

2.3 Thrust Area I – Building Systems

2.3.1 TA I Goals

The new Building Systems thrust area was created to bring focus to the research and implementation issues that were exposed but not completed in the building testbeds. Work on the Van Nuys and the U. C. Science testbeds illustrated the PBEE methodology developed by PEER. In these two assessments of existing buildings, researchers demonstrated the capacity of the methodology to integrate data from a hazard analysis into a structural analysis, and then to use the engineering demand parameters generated to calculate damage and assess losses in terms of repair costs, casualties, and downtime. These probabilistic assessments were then presented in a variety of formats for decision makers to engage in design and cost trade-offs.

The testbeds demonstrated the present capacity to complete each step in the process, but they also highlighted areas that need further research and development. The most important needs, which form the goals for the Building Systems thrust area for Years 8 to 10, are

1) to improve the capacity to model performance decisions (EDPs to DVs),
2) to benchmark the performance of new reinforced concrete frame and wall systems, and
3) to package the PEER performance-based engineering methodology in a way that makes it accessible to the engineering community. This is part of the outreach effort that will become a major aspect of the PEER effort for the next three years.

2.3.2 TA I Strategic Plan

To achieve the three-part goal, the research for Year 8 (as well as for Years 9 and 10) is organized around these three themes, as is outlined in the strategic plan chart in Figure 2.14. To make informed “Performance Decisions,” an engineer as well as an owner or facilities manager must understand the trade-offs involved in design alternatives in terms of up-front construction costs as well as probable repair costs, injuries to occupants, and time needed for recovery from damage. To improve the translation of engineering demand parameters to economic and human consequences we have three Year 8 projects focused on modeling consequences, and estimating losses from the benchmark study (PIs: Comerio [1202003-4], Miranda [1042004], and Meszaros [1062004]). On benchmarking, Deierlein [3362003-4] will continue work started in Year 7, with input from Lowes [3422003-4] on structural fragilities. Cornell [1052004] will finalize the Intensity Measure (IM) selection and ground motion scaling procedures, Stewart [1082004] will complete work on soil-foundation-structure interaction (SFSI), and yet to be designated PI(s) will complete simulations and modeling of shallow and deep foundation performance [1102004]. Krawinkler [1012004] will be responsible for the overall packaging of the methodology for practicing engineers, while May [1072004] will focus on the role of performance engineering in the regulatory systems and mechanisms for outreach for early adopters in the engineering community.

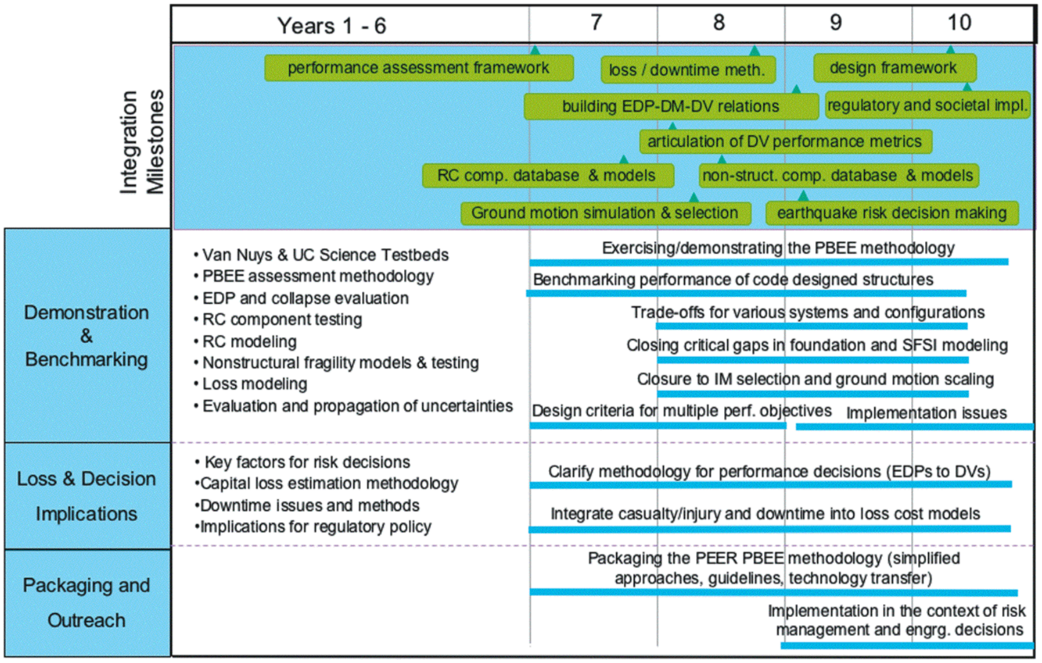

Figure 2.14 – Strategic Plan: Thrust Area I – Building Systems

2.3.3 TA I Critical Mass and Level of Effort

Overall, the Principal Investigators all will work across the spectrum of the performance equation, but each will contribute to the methodology as well as to specific benchmarking case studies. There is a critical mass in each area of emphasis: inputs to the structure (Cornell, Stewart, foundation modeler(s)), structural analysis and design (Deierlein, Lowes, Krawinkler), and loss assessment, performance decisions, and implementation (Comerio, Miranda, Meszaros, May).

While each Principal Investigator will be asked to complete specific components of the work, each is expected to coordinate and contribute to the overall thrust area effort. For example, the work of Cornell, Stewart, Miranda and Meszaros will contribute to the benchmarking study led by Deierlein. Comerio, Krawinkler, and May will focus on packaging and outreach, but each researcher will have a stake in the methodology development.

Below, each Year 8 research project is described briefly.

Comerio [1202003-4] is working on a method to estimate time needed to re-occupy a building based on factors unrelated to the repair of physical damage. These include the importance of the space to operations, the ability to finance, and the ability to secure “surge” space for construction. The approach will be articulated at the end of Year 7. In Years 8 and 9, the methodology will be integrated with casualty and cost estimating, with a specific focus on the translation from engineering demand parameters to loss consequences.

Miranda has developed a sophisticated method for estimating probable loss costs based on engineering demand parameters. In Year 8, he will apply the model to the benchmarking study and develop ways to simplify the analytic approach for comparing alternative design concepts [1042004].

Meszaros (and Ince) [1062004] will continue to work with Miranda to translate the results of the benchmark study to financial parameters comprehensible in the business area. Meszaros and Ince will formalize appropriate financial decision mechanisms needed from performance assessments.

There will be considerable coordination between these “performance decision” researchers and those involved in benchmarking and methodology development. The larger goal, not only in year 8 but throughout the work, is to clearly develop methods that translate engineering outputs into decision parameters—issues that force design and performance decisions.

May was funded in Years 6 and 7 to consider regulatory system implications of PBEE. These are published, and in Year 8 he will review the societal implications of PBEE—taking a systematic look at the benefits of performance engineering, particularly in the regulatory context [1072004]. This will include beginning to consider how PEER can best transfer PBEE to the engineering and regulatory community.

Deierlein [3362003-4] will conduct the lead project in the benchmarking effort. He will apply the PEER methodology and tools to assess the performance of RC frame and wall buildings that conform to current code standards. He will (a) benchmark the performance of building code complaint RC frames, (b) contribute to the development and “packaging” of the PBEE methodology and enabling data and technologies through their application to the benchmarking exercise, (c) conduct studies to use PBEE assessment tools to ascertain how building performance is affected by key design criteria for minimum strength, stiffness, and ductility, and (d) evaluate trade-offs, using the PBEE decision metrics, for various systems and configurations.

Cornell [1052004] will bring closure to the all-important issues of intensity measure (IM) selection and ground motion scaling. Included will be both scalar and vector schemes for IMs. Far and near-source situations will be considered. The recommended process will include record selection, recommended number and kinds of nonlinear time history analyses plus post-processing of response output.

Lowes [1092004] will continue developing EDP-DM-DV relationships for RC building structural components. The emphasis will be to develop improved models linking repair effort, including downtime required for repair, with earthquake damage to structural components. The primary deliverable will be a series of models defining repair effort as a function of the structural component damage state.

Stewart’s emphasis will be the integration of geotechnical/seismological uncertainties into a unified analysis of system performance [1082004]. The uncertainties that will be considered include epistemic uncertainty in the site hazard, aleatory uncertainty in the variation of ground motion from the free-field to the foundation (i.e., the so-called “kinematic interaction” effect), and aleatory uncertainty in the soil flexibility/damping associated with inertial soil-structure interaction.

Krawinkler [1012004] will take the lead in facilitating the use of the PEER PBEE methodology in engineering practice. His project is the first step of the building systems packaging/outreach program, whose objective it is to communicate the PEER methodology to the users. He will develop a set of “guidelines” to be followed in carrying out a performance assessment, summarize processes and data for simplified approaches for performance assessment, and summarize data and criteria that can form the basis for performance-based design.

We also have three placeholders for projects on loss modeling associated with the benchmarking study, nonstructural performance, and foundation modeling. For the loss modeling [1112004], we are awaiting results from work undertaken in Year 7, before we set the direction for linking loss costs, casualties and downtime into the benchmarking study. Similarly, on the soil/foundation modeling issue [1102004] we are holding back on defining a focused topic and assigning a specific PI until the Year 7 benchmark study has clearly defined the needs for modeling the soil/foundation interface for deep and shallow foundations. Finally, efforts to synthesize damage models and develop protocols for evaluating nonstructural components will be done in collaboration with outside researchers who are involved in the FEMA-supported ATC 58 project on PBEE [1122004].

2.3.4 TA I Research Advances and Deliverables

The new Building Thrust Area combines researchers from four of the five previous thrust areas—Loss Modeling and Decision Making, Geotechnical Performance, Assessment and Design Methodology, and Structural and Nonstructural Performance. This is similar to the structure of the testbeds, which also combined researchers across thrust areas. The advances made in each thrust area and in the testbeds shaped the decision to create the Building Thrust Area.

In the previous Thrust Area 1, Loss Modeling and Decision Making, the majority of the research focused on three areas: (1) Identification of decision making factors, (2) Gauging losses and costs, and (3) Loss Modeling. Work by several researchers identified what we called the "3Ds"—death, dollars, and downtime—as the key decision factors. Metrics were developed for measuring structural, nonstructural, economic, human and institutional losses by Beck, Chang, Comerio, Ince, Meszaros, Miranda, Porter, and Shoaf. The various approaches were applied in the Van Nuys and U. C. Science Testbeds. These have been published in numerous scholarly articles and documented in the testbed results. In Years 6 and 7 we developed a clear understanding of the economic framework needed for decision making, and basic approaches to estimating casualties and downtime. This work serves as the basis for the goals articulated for Years 8-10: to refine and simplify the methodology for understanding losses and making performance decisions.

In a parallel effort, May focused on the larger policy issues of adoption and implementation. His work up to Year 7 looked at performance standards in a societal context, including the barriers to adoption of performance standards as well as the implications of performance standards on regulatory systems. He has published several articles comparing performance standards in a variety of regulatory models. In Years 8-10, he will focus on broader societal benefits derived from performance engineering and mechanisms for outreach to "early adopters."

Similarly, in the previous Thrust Areas 2, 3, and 5, geotechnical and structural engineers developed and tested performance models for building systems. Much progress has been made in quantifying soil-foundation-structure interaction effects (Stewart), geotechnical uncertainties and their effects on engineering demand parameters (Kramer), and behavior of shallow foundations (Kutter and Hutchinson).

At the end of Year 6 most basic concepts of a comprehensive performance assessment framework have been put in place. Different methods for uncertainty propagation have been explored and evaluated, ranging from simple first-order second-moment approaches to full Monte Carlo simulation (Beck, Porter, Cornell). Work was performed on quantifying sensitivities and identifying those uncertainties that significantly affect the decision variables on which performance assessment is based (Der Kiureghian, Conte, Krawinkler). In Year 7, issues of performance-based design (Krawinkler) and benchmarking (Deierlein) have been growing in emphasis. At the same time, work on insufficiently resolved issues of performance assessment, such as collapse prediction (Krawinkler), casualty evaluation (Shoaf/Seligson), and EDP-DM-DV relationships (Beck/Porter, Lowes) are receiving specific attention.

Testing of the performance assessment methodology forms a crucial part of the development effort. For this purpose, two major efforts are in the research plan. One is the recently completed testbed program, which utilizes two building testbeds (the U.C. Sciences Building and the Van Nuys building) that have become the center of focused studies in which the PBEE assessment methodology has been tested, additional research needs have been identified, simplified approaches have been developed, and the socio-economic impact of different performance objective formulations has been demonstrated.

The second “testing” effort has been started in Year 7 and is expected to continue until Year 10. It is concerned with benchmarking and packaging the PEER PBEE methodology for buildings. This effort ties in with the needs of the community to carry out an assessment of the performance of buildings designed according to present code requirements. In this work we are selecting a small set of buildings, applying the PBEE methodology, and in the process finding out how the methodology has to be packaged in order to be useful to the engineering profession.

2.3.5 TA I Future Plans

In Years 9 and 10, the *Building Systems* Thrust Area will refine the work started in Year 8. This will include (1) a clear presentation of the PEER performance methodology through the benchmarking studies, (2) completion of the methodology for performance decisions in the translation of engineering demand parameters to decision variables, (3) simplified design and decision tools for practitioners, (4) continued investigations of policy and implementation hurdles, and (5) outreach strategies to enhance the adoption of performance-based engineering. At this time there are no plans to start a major new effort that has not been identified in the Year 8 research plan. The emphasis will continue to be on refinement, implementation, and packaging of the PEER PBEE methodology and on communicating the methodology to the users and stakeholders. From a more global perspective, the emphasis will be on outreach activities. But the door is open to innovative projects that will contribute significantly to improvements of the PBEE methodology and its impact. In Year 8 it is planned to solicit innovative ideas from PEER institutions and BIP members. An area that may receive particular attention is that of innovative concepts for performance enhancement. Also, a summary assessment is needed of presently available methods for estimating casualties. We have come to the conclusion that a rigorous quantification of the number of casualties cannot be achieved within the present scope, and we will have to look outside the PEER core research group to find the best qualified individual to summarize the state-of-knowledge in this important but most difficult topic.

2.4 TA II – Bridges and Transportation Systems

2.4.1 TA II Goals

The *Bridges and Transportation Systems* research program is directed toward further developing the performance-based earthquake engineering (PBEE) methodology developed by PEER and demonstrating its utility through application to difficult bridge design problems that integrate structural and geotechnical considerations. The testbed projects related to bridges (Humboldt Bay and I-880) demonstrated the application of the PBEE methodology to two very complicated, large bridge structures. The results were well received by business and industry representatives, but it was noted that the utility of the methodology now depended on its further development and implementation in simpler and more transparent procedures. This effort would require further clarification on the procedures and methodologies used to derive the various components of the overall methodology (fragility curves, damage measures, decision variables, etc).

The goals for the Bridges and Transportation Systems research program are therefore to: (1) further develop the PBEE methodology and package it in ways that are accessible to the engineering community, (2) demonstrate the PBEE methodology by applying it to variations on a more common bridge configuration, including cases involving the use of performance enhanced columns and cases involving liquefaction and lateral spreading hazards, (3) address the knowledge base and enabling technology needs for the above demonstration problems, and (4) advance our capabilities to model seismic risk for transportation and geographically distributed systems.

2.4.2 TA II Strategic Plan

The strategic planning graphic for TA II shown in Figure 2.15, defines a coordinated sequence of research projects to address the goals described above.

The research plan for Years 8 to 10 include four projects that involve demonstrating the PBEE methodology for variations from a common baseline bridge structure (Stojadinovic 2092004, Mahin 2022004, Kramer/Arduino 2032004, Bray 2042004/Martin 2052004). The variations that each demonstration project will address will exercise the methodology for very different purposes, thereby illustrating its usefulness in different ways. The researchers for each of these projects will work closely together, sharing components and models, and bringing different technical expertises to the group effort.

This group effort includes a lead project on clarifying, simplifying, and communicating the PEER methodology that includes a detailed report in Year 8 that clearly specifies recommended procedures for implementation of the PEER methodology for bridge systems (Stojadinovic 2092004). This detailed report will provide a synthesis of best practices that the other projects can utilize and build upon.

This lead effort on the methodology will be followed by a complete demonstration for a baseline bridge structure (Stojadinovic 2092004) that will be selected with input from our BIP representatives (Caltrans, TBA 2142004). The tentative baseline bridge configuration, based on discussions with our BIP representatives, is a three to five span bridge with earthen abutments and typical Caltrans detailing. By focusing on a single baseline bridge, this project will provide a

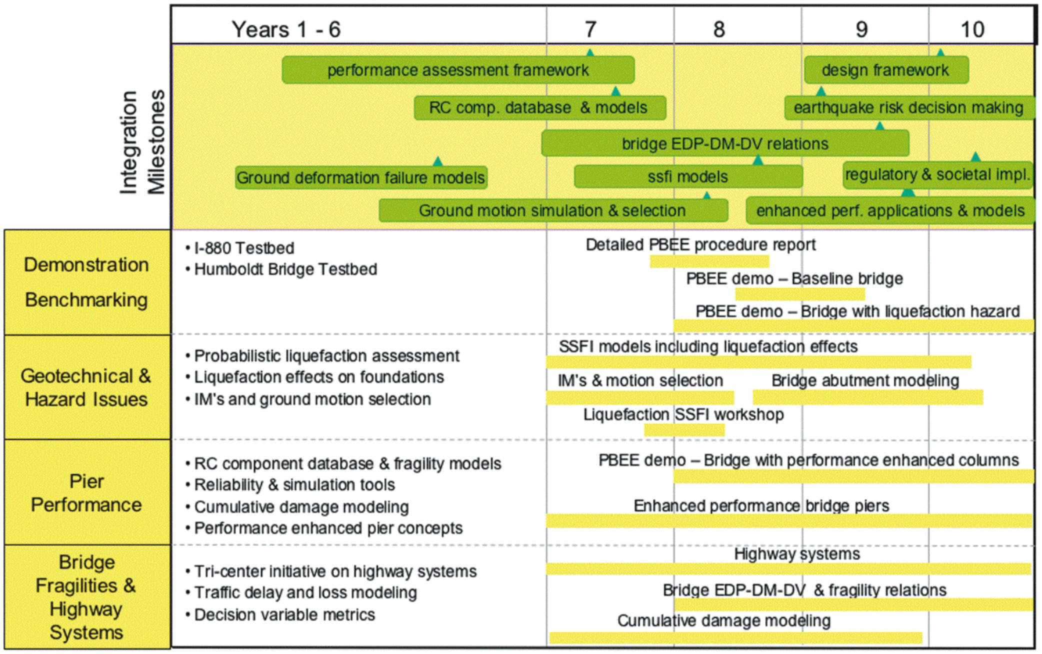

Figure 2.15 – Strategic Plan: Thrust Area II – Bridge and Transportation Systems

complete demonstration of the PEER methodology in advance of the other parallel demonstration projects, and therefore provides a framework for them to utilize and build upon.

The benefits of performance-enhanced piers will be evaluated using PEER methodology (Mahin 2022004), thereby illustrating both the utility of the performance-enhanced piers and the utility of the PEER methodology for evaluating new technologies. This project builds upon the experimental and computation efforts on performance enhanced piers, as described later. In addition, this project would address the impacts of near-field motions, for which performance-enhanced piers may be well suited.

The effects of liquefaction and lateral spreading on bridges will be evaluated through two parallel demonstration projects. The first project (Kramer/Arduino 2032004) will utilize continuum soil modeling capabilities in *OpenSees* as part of the numerical model of the bridge system. This project will consider the effects of varying soil conditions (thickness of liquefiable soil, relative density or penetration resistance for the liquefiable soil, etc.). This project will provide additional insights into the physical effects of liquefaction of bridge performance through the numerical modeling, and also demonstrate how the PEER methodology can effectively utilized in making informed decisions as to whether remediation is warranted or not for non-critical bridges.

The second demonstration project regarding liquefaction effects on bridges (Bray 2042004/Martin 2052004) will include the development of simplified design recommendations/procedures and the evaluation of alternative remediation schemes. This project will translate various PEER research findings into forms that are quickly adopted in design practice, and thus fill an urgent need for Caltrans and industry. In addition, this project will demonstrate how the PEER methodology can be effectively used with simpler design-level analysis methods to make informed decisions.

Fragility curves that relate damage measures to engineering demand parameters will be further developed in Year 8 for a broader range of structural components, as needed for the bridge demonstration projects (Eberhard 2072004). Fragility curves for implementation in transportation systems analyses will also be further developed (TBA 2132004).

Research on cumulative damage associated with low-cycle fatigue buckling and fracture of longitudinal reinforcement will continue in Year 8 (Lehman 2102004). This cumulative damage research will include testing and model development (Lehman 2102004) and computational implementations in TA IV (Kunnath 4062004).

The innovative idea of enhancing the performance of bridge piers by applying vertical post-tensioning will be further developed through experimental and analytical studies (Mahin 2022004, Billington 2082004). These studies are motivated by the observation that post-earthquake residual displacements are one of the primary contributors to bridge closure and replacement. The objective of the investigations is to show how post-tensioning, combined with mild steel reinforcement, can reduce residual drifts. The results of these studies will be fed into the demonstration project, wherein the utility of PEER methodology to evaluate new technologies will be demonstrated.

Experimental and computational studies of soil-foundation-structure interaction will continue for pile foundations in liquefying and laterally spreading ground (Boulanger 2012004, Ashford 2062004). Numerical analyses of the full-scale blast-induced liquefaction and lateral spreading tests funding by PEER Lifelines will continue in this year, extracting additional insights into the mechanisms of interaction and calibration of *OpenSees* (Ashford 2062004). In addition, dynamic centrifuge model tests will be performed for pile-supported abutments embedded in a laterally spreading soil profile (Boulanger, Lifelines project). These centrifuge tests are focused on evaluating the restraining effect that piles can have on abutment deformations, which is an important mechanism that designers are increasingly beginning to rely upon. Numerical analyses of the experimental data will contribute to calibration of *OpenSees* models and simpler design analysis models. These studies continue PEER efforts in advancing this field through parallel experiment, computational, and performance-based design projects.

Continuing advances in *OpenSees* capabilities will also support the bridge systems thrust area. Specifically, the advances in computational capabilities will be exercised by performing three-dimensional modeling of soil pile interaction in liquefied ground (Elgamal 4022004), for which the ability to do coupled modeling in *OpenSees* is essential (Jeremic 4092004).

In March 2005, a workshop will be held on emerging design methodologies for pile foundations in liquefied ground (Boulanger 2372003). This workshop will bring together engineering practitioners and researchers from across the U.S. and internationally to summarize the most current understanding of fundamental mechanisms, numerical modeling abilities, and design recommendations for practice.

Research on transportation systems will progress in several ways. Study of the treatment of uncertainties in the seismic risk analyses for transportation systems is continuing (Kiremidjian 3392003-4), and the economic losses that may ensue for travel disruptions will be studied for a Bay Area earthquake (Moore /Fan 3402003-4). The above analyses have shown that bridge fragility models are a major input that requires further development and thus another project will address that need (TBA 2132004). These efforts also contribute directly to tri-center collaborations (Moehle 3342003-4).

2.4.3 TA II Critical Mass and Level of Effort

The strategic plan brings together PEER researchers with the appropriate critical mass and expertise to achieve the goals for the *Bridge and Transportation Systems* thrust area. The four demonstration projects bring together six researchers (Stojadinovic 2092004, Mahin 2022004, Kramer/Arduino 2032004, Bray 2042004, Martin 2052004) with complementary skills, such that their close coordination and collaboration provides opportunities for more rapid advancements in the PBEE methodology and its packaging for the engineering community. The other projects provide support for the demonstration projects by addressing key knowledge base needs and enabling technology needs. For performance enhanced columns, the supporting projects include experimental and computational efforts by Mahin (2022004), Billington (2082004), and Lehman (2102004). For liquefaction effects, the supporting projects include experimental and computational efforts by Boulanger (2042004) and Ashford (2062004). In addition, the bridge demonstration project involving liquefaction effects will leverage past accomplishments by PEER researchers and their close connections with major efforts at MCEER and in Japan. Several *OpenSees* efforts will address needs for this thrust area (e.g., Elgamal 4022004, Jeremic 4092004, Kunnath 4062004). The work on EDP-DM-DV's by Eberhard (2072004) and bridge fragilities (TBA 2132004) provide support across all bridge demonstration projects, and the work by Kiremidjian (3392003-4), Moore/Fan (3402003-4), and Moehle (3342003-4) contribute to transportation systems and the tri-center initiative. All projects will benefit from the close communications with practitioners and Caltrans.

2.4.4 TA II Research Advances and Deliverables

PEER researchers have made significant advances in the areas that will contribute to the Bridges and Transportation Systems Thrust Area. The reorganization means that the past accomplishments and advances by researchers in this thrust area have come from across the spectrum of past thrust area designations.

The I-880 and Humboldt Bay bridge testbeds (Kunnath 4232003, Conte 4132003) demonstrated the application of the PBEE methodology to two very complicated, large bridge structures. These projects drew together findings from past PEER research efforts and were effective in pushing the implementation of the PBEE methodology and in identifying those areas in greatest need of development. The Humboldt Bay bridge testbed exercised newly developed *OpenSees* computational tools and illustrated the challenges of accounting for liquefaction effects across such a large bridge.

PEER research on liquefaction effects for pile foundations has made great advances, as this area was poorly addressed only a few years ago. Contributions have included original experimental data, identification of fundamental mechanisms of interaction, development of computational modeling tools, and guidance on simplified design methodologies (Boulanger 2312003, Ashford 2342003, Conte 4132003, Elgamal 2202003).

Advances have been made experimentally and computationally in performance-enhanced columns (Mahin 5342003, Billington 5362003) and cumulative damage in rebar (Lehman 5402003).

Damage models and decision models have been advanced, including an electronic on-line database of column tests and fragility relationships between *EDPs (*such as column ductility ratios, plastic hinge rotations, and strains) and damage states (Eberhard 5282003) and the translation of field damage observations into decision making for bridges (Porter 3262003).

The tri-centers initiative has advanced the network modeling of transportation and distributed network systems (Kiremidjian 3392003, Moore/Fan 3402003, Moehle 3342003) and identified key areas where improved fragility relations and inventory knowledge is needed.

2.4.5 TA II Future Plans

The future plans for the Bridges and Transportation Systems Thrust Area follow directly from the Year 8 plan through to Year 10. There are a couple of projects that may warrant redirection based upon progress in Year 8, but it is largely expected that the demonstration projects and the supporting projects will require extensions through Years 9 and 10 (depending on the project). The success of these demonstration projects will show that the PBEE methodology can be used to assess existing bridge design procedures, assess new performance enhancing technologies, and assess challenging geotechnical hazards like liquefaction. Having demonstrated the PBEE methodology in ways that are accessible to the engineering community provides opportunities for post-Year 10 efforts on utilizing the PBEE methodology for other classes of bridge structures, other technologies, and other hazards.

2.5 Thrust Area III – Lifelines Component & System Hazards

2.5.1 TA III Goals

The Lifelines Components and Systems research program is directed toward increasing the reliability and safety of geographically distributed lifelines systems including transportation and utility lifelines. The performance of a lifeline system governed by three considerations: (1) the regional distribution of earthquake ground motion and ground failure, (2) the performance of individual components to ground shaking and ground failure, and (3) the interaction among the multiple components of the lifeline system and the impact of damage on flow through the lifeline system. The research program is designed to address these aspects within the confines of a limited set of lifelines systems determined by the external funding agencies. At present, the lifelines systems are restricted to highway networks and electric and gas transmission and distribution systems.

The goals for the Lifelines Components and Systems research program are therefore to: (1) improve the ability to estimate distributions of strong ground motion considering the range of earthquake mechanisms, earthquake magnitudes, and path, distance, and site effects expected especially in coastal California; (2) improve ability to estimate extent of ground failures that may affect distributed and/or buried lifelines systems; (3) develop practical analytical methods including fragilities for assessment of performance of lifelines components including electric utility equipment and buildings (bridge substructures and superstructures are excluded, as they are covered under TAII and other programs); and (4) develop models for assessing system risk, use those models to understand where the greatest uncertainties and research benefits may lie, and query risk decision processes to better understand how to influence performance decisions about lifelines.

2.5.2 TA III Strategic Plan and Milestones

The strategic planning graphic for TA III (Figure 2.16) defines a coordinated sequence of research projects to address some of the goals described above. The plan, however, is not shown fully populated in future years in the same way as is done for the other thrust areas because of the different funding sources. TA I, II, and IV are funded by the NSF and core matching funds, whereas TA III is funded primarily by the Lifelines Program sponsors. Continuation proposals to those sponsors are pending, and it would not be appropriate to provide proposed details until funding decisions are made by those sponsors.

The research plan for Years 8 to 10 includes two main, multi-investigator projects on ground motions. The first of these will continue work to improve our ability to predict earthquake ground motion for design application through better attenuation relations. Work being completed during Year 7, referred to as NGA-E (Next Generation Attenuation – Empirical) culminates a major, coordinated effort to develop improved attenuation relations for horizontal ground motions based primarily on empirical ground motion data (1A03, 1L01-1L10b). The next phase, NGA-H will involve a hybrid of empirical and simulation data. It will add new attenuation relationships for subduction earthquakes (relevant to northern California), vertical motions, and additional 'intensity measures' beyond elastic response spectra (e.g., duration, inelastic spectra, etc.). The results should significantly improve estimates for near-field and basin conditions through incorporation of emerging major advances in earthquake simulation. It also will add a "fling step" model that accounts for relative timing of static offset motions with vibratory shaking.

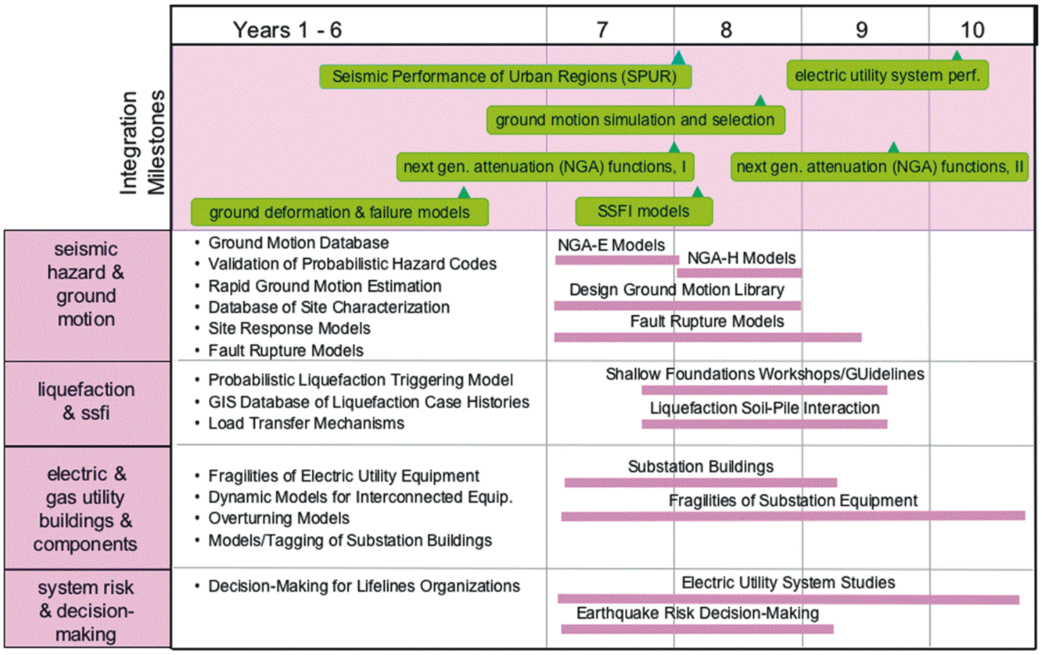

Figure 2.16 – Strategic Plan: Thrust Area III – Lifelines Component & System Hazards

The second project on ground motions will produce a Design Ground Motion Library (DGML). The project aims to develop convenient, standard, and transparent methods for selection and scaling of earthquake ground motion histories for use in non-linear dynamic structural analysis. Design application of non-linear analysis for lifeline structures is expected to increase in the next several years, especially for cases involving near-fault locations, unusual structural geometries, or special details including energy dissipation devices. Current selection procedures have proven unreliable, demonstrating the need for improved standard procedures are needed. While this activity is being driven by the lifelines applications in TA III, the work will be coordinated closely with the other thrust areas where the same product is needed.

An additional project on seismic hazard will develop a fault rupture model to improve our ability to predict earthquake fault surface-rupture displacement for design application to bridges and other lifelines crossing fault zones. The new design tools are being designed to account for the distribution of offset as a function of distance from the mapped fault, and account for variations in mapping uncertainty, the distribution of slip along fault strike, the likelihood of secondary faulting, and the size of the facility footprint. This work will be an extension of ongoing work that has established the fundamental methodology and will provide an initial design tool for strike-slip earthquakes. This next phase will add a new model for reverse faults and improve on the Phase-1 model for strike-slip faults by better accounting for recognized zones of rupture complexity (e.g. fault bends, step-over zones).

In the area of soil liquefaction and SSFI, work will continue in the US and Japan to improve our ability to predict earthquake ground deformation caused by liquefaction and to develop improved methods for evaluating the SSFI impacts of liquefaction deformations on bridge foundations and abutments. Earlier work in TA III included significant advances in predicting liquefaction demands and better SSFI modeling of loads imposed by liquefied ground. The liquefaction demands research has yielded a comprehensive suite of triggering assessment techniques, demonstrated the potential for regional deformation mapping, and initiated work on improved prediction of lateral spread displacements. Related SSFI modeling research has provided unprecedented experimental data sets from both full-scale field experiments and a range of centrifuges and shake tables to serve as new constraints on numerical models. In the next phase, SSFI research will focus on synthesizing the array of experimental findings, filling remaining data gaps, calibrating numerical models, and developing practical design guidelines. Liquefaction demands research will focus on completion of improved displacement estimation tools.

In the area of electric and gas utilities buildings and components additional work is anticipated in the area of substation buildings and equipment. In the area of buildings, ongoing studies by two of our BIP partners (Maffei 508 and Malley 509) are evaluating the practicality of work completed to date. Recommendations from those studies are expected to provide guidance on future needs. Similarly, the recent meeting of the Inter-Utility Seismic Working Group (convened at the request of PEER) is providing guidance on specific electric utility distribution equipment for continued study, which we anticipate will guide our work in this area in the next three years.

In the area of system risk and decision making, the IUSWG has recommended that, in addition to continuing work on other tasks mentioned above, PEER should conduct a sensitivity study of a utility system to identify those areas where there is greatest uncertainty and where research could have biggest payback. We anticipate that this will be an early project in the next phase, which will build on the previous work of Ostrum (413) and Werner (601), and contribute to tri-center research discussed in Volume 3. The early study of earthquake risk decision-making (604) will be expanded in project 605, where we will endeavor to broaden the number and types of lifelines organizations included in the study.

2.5.3 TA III Critical Mass and Level of Effort

Since its inception, the lifelines portion of the program has involved researchers both from within and outside the Core Universities. In the case of the NGA projects, we have involved five of the leading attenuation relation developers; 1- and 3-D ground motion simulation experts from PEER, SCEC and others; practicing engineering seismologists; and an international team of researchers providing data on ground motions and site conditions. In addition, the work has been guided by a series of two-day workshops involving typically 40 to 50 researchers and practitioners. Work on liquefaction and its effects on foundations has involved PEER researchers (e.g., Seed, Elgamal, Ashford, Boulanger) working in collaboration with international partners to leverage ongoing activities. Studies of earthquake risk decision-making will involve lifelines organizations and may be conducted by one of the researchers who has been active in another thrust area. Finally, work will continue to be conducted as part of the Tri-Center activity described in Volume 3.

2.5.4 TA III Research Advances and Deliverables

PEER has made important advances in previous research in this topical area. We have assembled the premier strong ground motion database, consistently processed with detailed information on site, distance, and rupture mechanisms, and made it widely available to the community online. Progress improving ground motion simulation techniques has enabled us to begin to fill gaps especially for large M and small distance. The first phase of the NGA project will produce improved models for attenuation relations around October 2004. This work will support ongoing studies in other thrust areas, as well as earthquake engineering research and practice worldwide.

In the areas of ground failure we have gathered and made available extensive data sets from laboratory and field research, which is providing a basis for new triggering models, some of which have been produced through PEER research and result in significant reduction in uncertainty. We have gathered important data on interaction between piles and liquefied, flowing soils that will serve as a basis for continuing development in Years 8-10.

Research on utility components has produced standards for testing as well as fragility relations for critical equipment, overturning models, and models for equipment interaction, all of which are widely used by utility companies in the western US. Work on utility buildings has led to new concepts on building tagging and building evaluation that currently are being tested by practicing engineers.

Deliverables for the next phase of research have been described in Section 2.5.2, and includes new attenuation models, liquefaction triggering models, models for ssfi interaction for foundations in liquefied soils, and improved models for electric utility components and systems.

2.5.5 TA III Future Plans

The future plans for TA III follow directly from the strategic plan and milestones described in Section 2.5.2. Details of the funded projects will be determined by the level of funding and the decisions of the Joint Management Committee working in collaboration with the PEER Research Committee. We anticipate that the next phase of Lifelines Program research with extend through Year 10, with new strategic planning taking place during the intervening years to ensure continuation of funding beyond Year 10.

2.6 Thrust Area IV – Simulation & Information Technologies

2.6.1 TA IV Goals

A central requirement of PEER's research mission on performance-based earthquake engineering methodology is the need to simulate the performance of structural and geotechnical systems. The simulation models must represent the modes of behavior and types of damage that are ultimately important in framing decisions for stakeholders. There are substantial problems and open questions on how to model the highly nonlinear behavior of structural systems with degrading components, or soil undergoing large deformation because of liquefaction, or the interaction between foundations and soils during large deformation. To address these substantial challenges, the rapid advances in information technology can be used in developing the next generation of earthquake engineering simulation applications and also educating the next generation of earthquake engineers. These advances include high-end computers for solving large-scale problems; databases for searching for new information from experimental data, simulation data, or observed data such as ground motion and field data; visualization technology for providing engineers, design professionals, and stakeholders understanding about the performance of their systems.

The goal of Thrust Area IV is to develop new simulation models and methods for performance-based earthquake engineering assessment and design methodologies, develop modern simulation software tools taking advantage of information technology advances, deliver the software tools to the community, and educate students in simulation methods and information technology applications in earthquake engineering. The goal of this thrust area continues through the re-organization of the research program in Year 7 with the application focus spanning building systems (TA I) and bridge systems (TA II). Lifeline systems are considered to a lesser extent, but provide a fertile future area, particularly as lifeline systems research moves towards consideration of lifeline networks. The incorporation of uncertainty in the simulations is essential, and the research in this thrust area has resulted in important developments in the methods and software for reliability computation.

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

As an advanced platform for computational simulation, *OpenSees* provides an important resource for the National Science Foundation-sponsored George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES), and it has now been adopted by NEESgrid System Integration project as the NEES simulation component. The NEESgrid decision to utilize *OpenSees,* and adapt it to the Grid, will increase the user base and range of simulation applications for the software. The modular design of *OpenSees* means that it can be customized for integrating physical and computation simulation through data repositories, visualization, and hybrid control for advanced experimental methods, all of which meet important NEES objectives. With community support, *OpenSees* provides long-term opportunities that include: (i) improving model-based simulation using data from advanced experimental facilities, (ii) extensions to include grid-based and other high-end computing for earthquake engineering, and (iii) integration with structural health monitoring systems using widely distributed MEMs sensors and processors.

2.6.2 TA IV Strategic Research Plan, Milestones and Deliverables

Figure 2.17 shows the strategic research plan for TA IV, emphasizing Years 7 to 10 and identifying the system-level integration milestones. The first six years of research in the thrust area were largely devoted to the development of new models and computational methods needed for structural and geotechnical simulation and implementation in the *OpenSees* software framework. The testbed projects in Years 5-7 provided an opportunity to expand the usage of *OpenSees*, identify problems as it was used for simulation in the building and bridge testbeds, incorporate improvements, and identify future research and development needs. *OpenSees* is currently in version 1.5, which has been used in the testbed projects. As a result of the testbed experience, improvements have been made in solution robustness, testing combinations of modeling options, analysis algorithms, and solution methods. The resulting improvements will be released near the end of Year 7 as version 1.6. Research in Year 7 also addressed high-end computing and hybrid experimental methods using the simulation technology, and visualization, all of which are important for NEES.

For Years 8 to 10, the strategic plan for TA IV is divided into three categories: Modeling, Simulation System and Platform, and Integrated Applications. These areas are described below.

Within the Modeling category, there is a thrust to complete the structural models for degrading cyclic behavior of RC components (including shear interaction in columns and joint behavior); improve models for low-cycle fatigue, bar buckling, and fracture, and understanding how these behaviors are affected by loading history; modeling of RC systems at incipient collapse; and validation of system models using experimental data such as from shake table tests. The other modeling thrust is to develop improved models for nonlinear response and soil liquefaction suitable for large-scale simulation, with substantial challenges in modeling SFSI for large-diameter shafts and bridge abutments to address needs in TA II. These two areas among others remain a topic for further experimental research and computational validation, and include major 3-dimensional reponse mechanisms, that must be accounted for. Results of this research will provide insights that can translate into design revisions, will most significant economical outcomes (in view of the involved large expenditures on these two bridge components). Overall, the modeling research contributes to the milestones SFSI, EDP-DM-DV relations for building and bridge systems, and enhanced performance models.

The second category is Simulation System and Platform. Through the collaboration between PEER and NEESgrid, we will integrate *OpenSees* with the NEESgrid data repositories. This will provide *OpenSees* users the ability to access NEESgrid data on experiments and simulation data, and to upload simulation results into the repository. In addition, we will address what has become an important need: providing integrated PBEE tools based on advanced simulation. To meet this strategic need, Year 8 will commence a new project on the development of software tools that include major elements of the PEER methodology, such as hazard definition, modeling and simulation, computation of fragility curves, sensitivity, and incremental dynamic analysis. The software packages will be applied to specific problems, such as soil site response, bridge foundations, and building frames, which are important deliverables and methods of dissemination for PBEE methods. The PBEE software tools will be designed to be modular and extensible for growth in their functionality over time.

2.6.3 TA IV Critical Mass and Level of Effort

The research team for TA IV includes experts on modeling for reinforced concrete components and systems and modeling geotechnical systems. For development of the software framework, several of the thrust area researchers have computer science backgrounds and in many cases collaborate with computer scientists on research related to the simulation framework. As the simulation methods are being used in the bridge and building testbeds, PEER researchers and industry partners are providing feedback on the effectiveness of the research products in simulation and usefulness of the databases.

One of the weaknesses sited in a previous site visit review and report was inadequate support

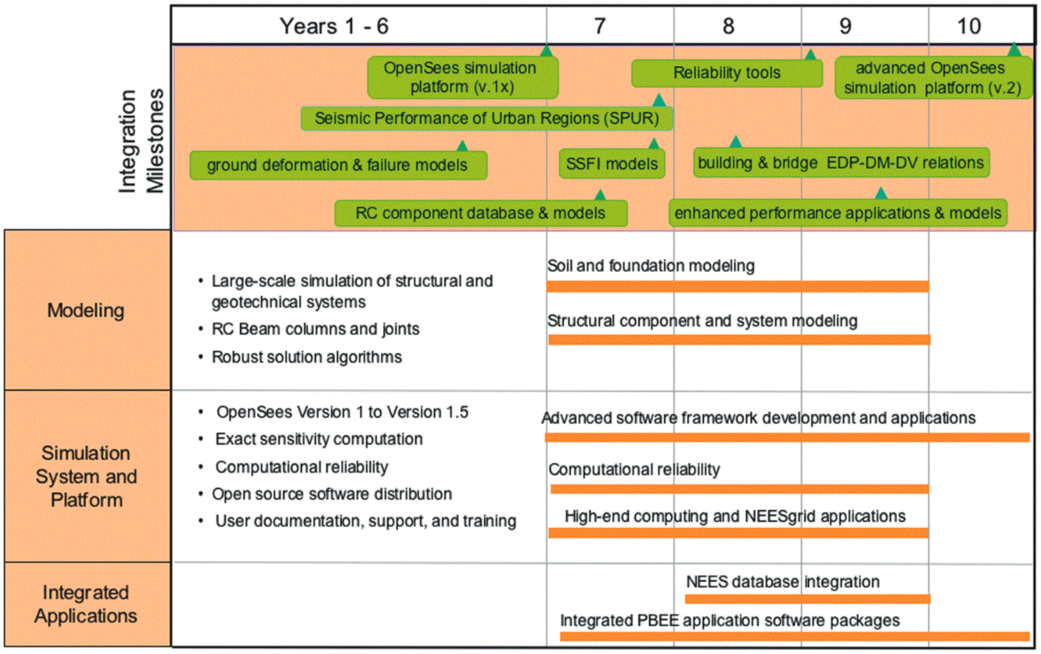

Figure 2.17 – Strategic Plan: Thrust Area IV – Simulation & Information Technologies

for information technology, computer science, and visualization. It should be noted that many of the graduate students conducting research in the thrust area are taking courses in computer science, generally as a minor program of study. This breadth of graduate education in computer science is unusual in earthquake engineering, and it has brought new technology and computer science methods into the PEER research program. Additionally, a number of thrust area researches have extensive experience in computer science and a track record of working with computer scientists. In the past year, two specific collaborations have been undertaken to provide computer science expertise. The first collaboration is with Dr. Michael Bailey of the San Diego Supercomputer Center in a project on scientific visualization for structural and geotechnical systems [4182003]. Bailey is looking at stereoscopic visualization methods and new ways to show stress, strain, and energy fields in continuum models for soils and frame models for structures. This project builds upon initial work of Bailey on structural systems (with Fenves) and soil systems (with Elgamal).

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

In the past year, we have developed important collaborations with the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). The NEES system integration project has selected *OpenSees* as the simulation component for NEESgrid. In addition to the core simulation capability, PEER is contributing to the development of data models for simulation data for use in NEESgrid data repositories, a web-based portal for simulation services, and porting of *OpenSees* to grid-based computing resources. After the NEESgrid software is completed, the NEES Consortium has proposed to provide ongoing maintenance and operation of the simulation component. This support, along with PEER's continuing commitment to simulation and information technology, will expand the users and development opportunities for *OpenSees*.

2.6.4 TA IV Research Advances and Deliverables

Highlights of accomplishments in Year 7 include:

- Soil-foundation-structure interaction in bridge systems, including deep foundations in liquefiable soil and new research on shallow foundations.
- Component models for reinforced concrete with an initial examination of damage measures for performance evaluation.
- Simulation for reliability computation, including exact computation of response gradients for highly nonlinear systems.

- Database applications to support simulations for the testbed projects.
- New scientific visualization method and software for structural and geotechnical simulations.
- Collaboration with seismologists and computer scientists to develop an integrated methodology for understanding the Seismic Performance of an Urban Region (SPUR).
- Application of *OpenSees* to hybrid experimental-computational simulation, including use of grid-based communication.

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

TA IV researchers worked closely with the Humboldt Bay bridge testbed team on the models and simulations for SFSI (Conte, 4132003, and related development by Elgamal, 2202003). The robust solution methods in *OpenSees* were particularly valuable because of the complexity of the soil models for liquefaction. The other bridge testbed on the I-880 viaduct (Kunnath, Year 6) used the nonlinear beam-column models, including a validation study, and the soil-foundation-structure interaction models developed in Thrust Area 2. The building testbed project on the Van Nuys building (Lowes, Year 6) used the shear models in the nonlinear beam-column elements and a recently implemented RC joint model (Deierlein Year 6). The *OpenSees* scripting facilities allowed parameterization of the models for a large number of cases. The fourth testbed project on the UC Science building (Mosalam, Year 6) conducted extensive analyses of the building for floor acceleration records used in the shaking table and analytical studies of non-structural component performance.

In two other collaborative application studies, *OpenSees* models are being evaluated against test data from large-scale experiments. In one case, soil continuum models for simulating ground deformations are being evaluated against a large-scale test in Japan, where explosives were used to trigger liquefaction in a test field containing pile foundations and a buried pipe (Ashford 2342003). In the second case, *OpenSees* frame models are being validated against a full-scale pseudo-dynamic frame test, results of which are made available through collaboration with the National Center for Research in Earthquake Engineering (NCREE) in Taiwan (Deierlein, Year 6).

Year 7 has seen the completion of a number of efforts for the models and computational features of *OpenSees*. A range of hierarchical models for beam-column elements is now available, including flexure, axial, and shear effects (Fenves and Filippou, 4212003) and generalized hinges (Deierlein, Year 6). The models include material and component behavior for cyclic degradation and large-displacement analysis. To support reliability and other applications, a new efficient algorithm for computing the response sensitivity for force-based elements has been developed and implemented (Fenves and Filippou 4212003). To solve large-scale systems with degrading components, a new quasi-Newton solution method based on a Krylov subspace has proven to be very efficient and robust when used in the testbed projects.

Continued progress has been made with integrating reliability computation into *OpenSees*. Der Kiureghian (4212003) has extended the first-order reliability method, many of the element and material models now support direct differentiation for computing response sensitivities for reliability computation. The research has also made progress on importance sampling for Monte Carlo simulations and extending a library of distributions and correlation structures for random variables. Conte (4132003) has been using these methods to begin probabilistic evaluation of the Humboldt Bay bridge with the completion of a complete model of the SFSI system. In addition, significant sensitivity analysis procedures are been developed this year for a class of nonlinear plasticity-based soil models for seismic applications. Progress on these projects responds to concerns raised in previous years' site visit reports about the need for reliability tools in *OpenSees*, which facilitate application of the PEER PBEE methodology and are not generally available in other earthquake analysis software.

2.6.5 TA IV Future Plans

Support and continued development for *OpenSees* will continue as a high priority, given the central role *OpenSees* plays as an enabling technology in PEER. During Year 8, the identification of capability and software design for version 2.0 will commence and efforts to grow and support the expanding user/developer base will continue. Most of this support is through the core development staff of research engineers at Berkeley (Fenves 4102003-4).

Model development for RC members will continue with conclude with completion of shear-flexure-axial interaction models (Filippou 4082004), continuation of advanced models for cyclic degradation of RC members including low-cycle fatigue (Kunnath 4062004). There will be increased focus on RC building systems, with new research on simulation for incipient collapse (Mosalam 4072004) and validation of system models using shake table data (Moehle 5252003-4). For geotechnical models, Elgamal (4022004) will begin research on modeling and simulation of large-diameter pile shafts and abutments for bridge systems, and Jeremic (4092004) will develop coupled (solid-fluid) models for liquefiable soils and large-scale simulations. These efforts integrate the structural and geotechnical elements of *OpenSees* and address topical challenges in seismic SFSI research. Conte (4032004) will conduct such integrated studies (PBEE framework applied to the Humboldt Bay bridge Testbed), and further introduce sensitivity analysis tools for geomechanics applications.

Computational reliability research will continue with Der Kiureghian (4042004) beginning research on non-ductile systems based on the completion of methods for ductile systems, and Conte (4032004) developing reliability methods for large-scale models of SFSI systems.

A new project (4102004) will be initiated to developed PBEE tools that integrate simulation models and methods for specific problems (e.g. site response, bridge pier, and building frames) with methods for moving from the hazard (IM) to at least damage measures (DM). The software will be designed to be modular and extensible. Collaborative work with the SPUR project and NEESgrid will continue as they have in Year 7.