SCIENCE PLAN – NHEIR@UCSD

Scientific Vision. To build a disaster-resilient and sustainable environment [1] system-level investigations of the performance of buildings, critical facilities, and lifelines are essential. In this effort, high-fidelity computational simulation models can be indispensable tools for design, performance assessment, and rational decision-making. Nevertheless, even the most sophisticated computational simulation tools available today do not have the required predictive capabilities to be used with confidence. Pertaining to earthquake engineering, the development of reliable computational tools and effective disaster prevention strategies necessitates concerted research efforts, spanning from basic material science to component behavior characterization to the system-level understanding of the response of structures to earthquakes, including non-structural components and soil-foundation-structure interaction (SFSI), as shown in Figure 4-1. Even though the need for such a holistic approach has been well recognized by the scientific and engineering communities, neither sufficient resources nor enough efforts have been dedicated to accelerate this process. While advanced numerical methods and material constitutive models have been developed in computational mechanics, only a relatively small number of these models have been validated for the simulation of structural, geo-structural and soil-foundation-structural behavior at the component or subassembly level, and even fewer have been proven at the system level. The absence of reliable and validated computational simulation tools means that pertinent experimental studies are needed to validate new design concepts, construction methods, and design codes, and equally important, to provide data about the performance and safety of the existing built environment. Furthermore, system-level performance tests are required to improve and validate high-fidelity physics-based computational models that are under development and that will progressively reduce the need for physical experiments ([3] and [4]). However, experimental data on the behavior of full/large-scale structural systems under extreme earthquake loads are scarce. The shake table at E-Defense in Japan and the Large High Performance Outdoor Shake Table (LHPOST) at UC San Diego are the only two active facilities in the world that can perform seismic performance tests on full-scale structural, geo-structural and soil-foundation-structural (SFS) systems with realistic earthquake input. Data from landmark tests conducted at the LHPOST facility in the last decade have already made tremendous impact on engineering practice in the U.S.

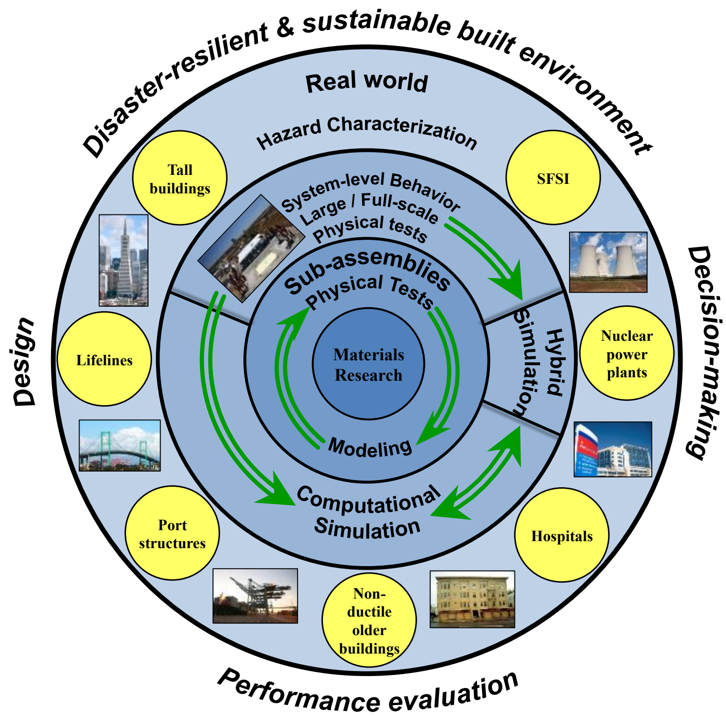

Figure 4-1. Research to attain disaster-resilient & sustainable built

Through the Experimental Facility at UC San Diego, NHERI will provide unique opportunities for collaborative research to enhance the disaster-resilience and sustainability of the built environment. NHERI@UCSD will offer a world-class, one-of-a-kind high-performance experimental facility, the LHPOST, to conduct research to enhance the understanding of the fundamental mechanisms governing the behavior and resistance of civil infrastructure systems and components to extreme earthquake loads. It will allow experiments at scales and loading conditions closely representing the real-world. Data gathered from these experiments will further enhance design codes and existing methods of analysis, and will enable the development of the next-generation design methodologies, modeling capabilities, and damage mitigation strategies.

Grand Challenges in Earthquake Engineering Research. The mechanical behavior of most civil infrastructure systems under extreme earthquake loads is highly nonlinear and complex, and varies significantly depending on the structural type and detailing, construction materials, and regional constructional practice. Unlike aerospace structures, civil structures cannot be prototyped for mass production or designed to remain within the elastic limit during severe load events. To ensure that structures of different types, system properties and materials have a consistent level of safety and predictable performance in earthquake events, a performance-based design (PBD) approach was extensively developed in the mid-1990s ([5] through [10]). It is based on a structural reliability framework and enables engineers to design structures and facilities to meet specific performance objectives with quantifiable and acceptable risks of (i) exceeding various damage states, (ii) casualty, (iii) loss of occupancy (downtime), and (iv) economic losses in future earthquakes. This methodology has been extended to other engineering fields such as blast engineering [11], fire engineering [12], tsunami engineering [13], wind engineering ([14] through [17]), hurricane engineering ([18] and [19]), and aerospace engineering ([20] and [21]).

Although the PBD methodology has not been fully implemented in practice, it has found its way into seismic design codes such as ASCE 7 [22] and the International Building Code [23] for new buildings, and into guidelines such as ASCE 41 [24] for the evaluation and retrofit of existing buildings. Notably, the risk-targeted seismic hazard maps [24] recently introduced in ASCE 7 [22] and IBC [23] rely not only on probabilistic seismic hazard data but also on structural fragility functions to achieve a uniform risk of structural collapse across the U.S. Furthermore, the recently developed and adopted FEMA 695 Methodology [26] that quantifies structural performance factors for new structural systems to be designed with ASCE 7 is also based on the notion of a uniform and acceptable risk of collapse. It is noteworthy that the development of reliable fragility functions, which are central to PBD, requires relevant experimental data or high-fidelity simulation models that are able to predict the nonlinear behavior of structural materials, components and systems under different hazard scenarios.

The seismic response of structures involves complex physics of heterogeneous materials with highly nonlinear constitutive properties and depends on the boundary/interface conditions such as the interaction between the structure and the supporting/surrounding soil. There are many open and profound issues and questions regarding how to accurately model these phenomena at the different length and time scales over which the physical processes develop. There are significant knowledge gaps about the seismic response of structures that have been damaged or have partially collapsed and their possible failure modes as identified in the NRC report [27]. State-of-the-art nonlinear structural analysis methods are still fairly limited in their ability to model nonlinear dynamic response of structures, especially when approaching collapse [28]. Failure is often triggered by localized strain concentrations resulting in stiffness and strength degradation that is sensitive to loading history. Examples of such behavior include local buckling and fracture in steel (both structural steel and reinforcing steel in concrete), shear failures in reinforced concrete (R/C) columns and walls, and connection or splice failures. Over the past few decades, significant experimental research has been performed on individual structural components (e.g., beams, columns, slabs) and subassemblies (e.g., beam-column joints, beam-slab-column joints) at various scales (all the way to full-scale) in the U.S. and other countries. The boundary conditions imposed on these test specimens may not be realistic as compared to their actual boundary conditions within the structural systems. The scale of these physical models can also be an issue since some design details, construction materials, and damage and failure mechanisms cannot be accurately reproduced in reduced scale models. These include the spacing of reinforcement in concrete structures, the size of aggregates in concrete, the quality and properties of welds, and the degree of plastic strain or damage localization, all of which can affect the ability of a structure to sustain inelastic deformations and the failure mechanisms.

Figure 4-2. Damage of R/M Building in

While computational models with various degrees of sophistication, e.g., beam-column finite elements (FEs) with lumped or distributed uni/bi-axial plasticity, plate and shell FEs with multi-axial plasticity/inelasticity, and 3D continuum FEs with inelastic material constitutive models, have been developed and calibrated with data from structural component/subassembly tests, numerically capturing the nonlinear structural component behavior and the interaction of structural and non-structural components up to incipient collapse and beyond remains a challenge. Figure 4-2 shows the brittle shear failure of a reinforced masonry (R/M) wall pier during the 1994 Northridge earthquake. Depending on the geometric configuration and boundary conditions, wall systems designed and detailed according to current code provisions can exhibit this kind of failure behavior under extreme earthquake loads [29] and [30]. Hence, the ability to model and predict such behavior through severe strength degradation to incipient collapse is of critical importance for PBD and safety assessment of new and existing R/C and R/M buildings [31]. It requires refined computational models that are able to accurately represent all the intricate mechanisms in the damage process, including the fracture of the concrete or masonry material, and the bond-slip behavior and the dowel action of the reinforcing steel, which can influence crack opening and the residual strength of a damaged wall. The performance of such a system can also be influenced by the strength and stiffness of the horizontal diaphragms and orthogonal walls. Hence, full-scale structural system tests, such as that shown in Figure 4-3, are essential to identifying and overcoming modeling deficiencies and validating these models and design details.

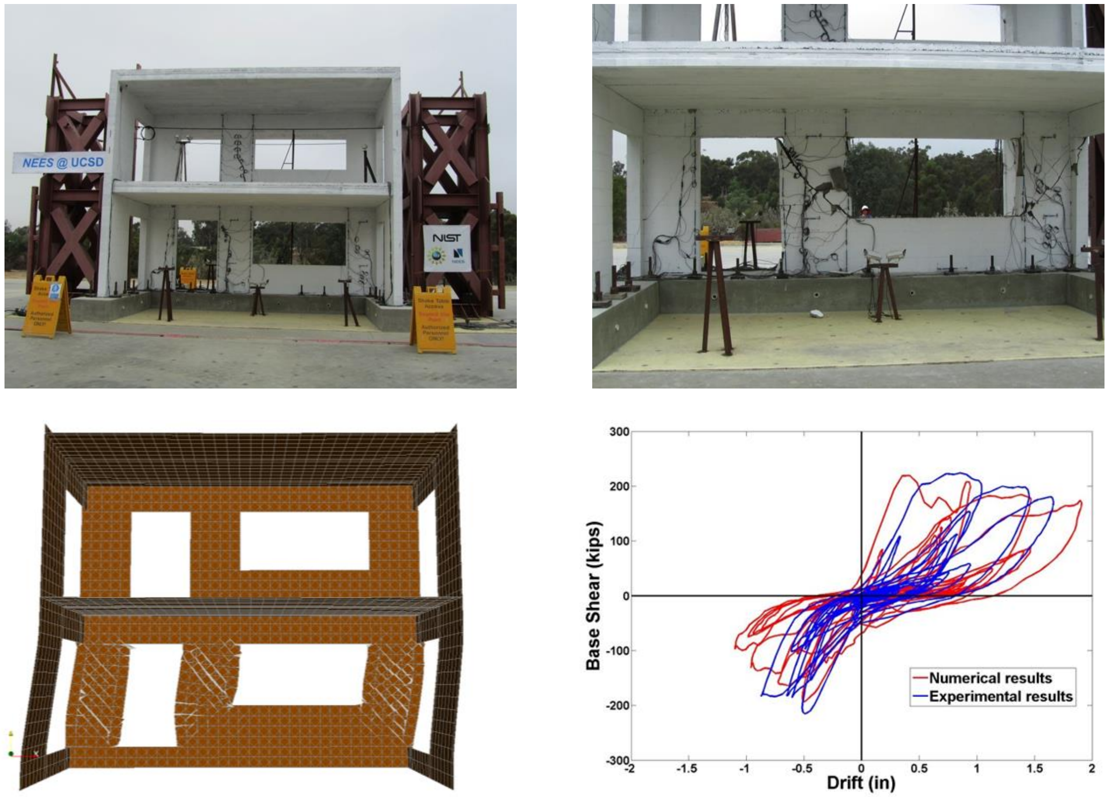

Figure 4-3. Validation of Design Details and Computational Simulation Models with Full-scale R/M Building Tests

Key Research Questions and Potential Technical Breakthroughs in Earthquake Engineering. The LHPOST at UC San Diego can be used to address the following key research questions, which will lead to high-impact technical breakthroughs in earthquake disaster prevention.

- ***How will existing older (wood, concrete, masonry, and steel) buildings, which were not designed and constructed according to current codes and construction practice perform in future earthquakes?*** Preservation of existing infrastructure systems is essential to attaining the disaster resilience and sustainability of the built environment. Past earthquake events in the U.S. and around the world repeatedly demonstrated that the vast majority of structural collapses in any seismic event have been associated with older structures. Factors leading to such poor performance include inadequate load transfer mechanisms, low-quality materials, inadequate connection details, limited ductility of structural elements, excessive interaction between structural and non-structural elements, and limited system redundancy. The development of adequate databases and reliable computational tools to evaluate the earthquake performance of these older structures so as to accurately identify the "killer" structures is of critical importance to ensuring life safety and disaster-resilient communities.
- ***How effective are new and existing seismic retrofit and mitigation techniques and post-earthquake repair methods for building structures and critical facilities?*** Identifying and improving the effectiveness of economical seismic retrofit methods will encourage building and facility owners to adopt such measures and upgrade deficient structures to meet current safety standards. The performance of a retrofitted structure is often governed by the interaction and connectivity of new and existing materials and components in the system. This often presents a challenge in computational modeling. Sometimes, localized retrofit or strengthening of structural elements produces unexpected

behavioral outcomes at the system level. Hence, system-level testing provides the ultimate assurance of the effectiveness of these measures.

- ***How well do structural systems designed according to current code standards perform in earthquakes? Can their damage and failure mechanisms be reliably predicted? Do they have an acceptable margin of safety against collapse?*** Current seismic design provisions are largely based on experimental data from structural component and subassembly tests as well as field data from past earthquakes. The behavior of structural components in a system can be quite different from that observed in laboratory component tests. This may be due to varying boundary conditions and/or interaction with other structural or nonstructural components. The next-generation PBD code provisions will focus on the system-level performance as predicted by computational simulation models, which have to be calibrated with available experimental data. Testing large-scale structural and SFS systems will provide critically needed data to assess how existing code provisions measure up to new performance criteria and to calibrate computational simulation models.
- ***What are the effects of SFSI on the performance of structural systems?*** SFSI can be beneficial or detrimental to the performance of structures during earthquakes. Design guidelines considering these effects are mostly based on analytical models, computational simulations, small-scale shake-table experiments in centrifuges, large-scale field testing of pile and slab foundations, and field observations from past earthquake events. Large-scale field testing provides pertinent data to calibrate soil properties in analytical and computational models; however, it cannot conclusively validate how SFSI affects structural response during an earthquake, because these tests neglect the dynamics of soil response during earthquake shaking and the inertial interaction with the superstructure. Moreover, they are generally at amplitudes lower than design target earthquake demands. The scale of SFS specimens in centrifuge tests has to be necessarily very small. This means that detailing of superstructure elements and materials for these tests necessitates simplicity due to the small scale. Therefore, results of such tests will have limited accuracy regarding the behavior of the actual structure or foundation. Shake-table tests used in combination with large soil boxes and reasonable size foundation and structural models are needed to complement centrifuge tests to validate corresponding computational models. These types of tests can also be used to study the performance of underground structures, bridge abutments, earth retaining walls and slope stability in hillside construction.
- ***How successful are innovative structural systems, materials, construction methods, design concepts, and response modification devices at delivering their targeted system-level performance?*** Through years of research, current seismic design and construction standards more or less satisfy the life-safety design criterion. To move towards a sustainable and disaster-resilient community, methods and techniques to minimize structural and non-structural damage, post-earthquake downtime and repair cost, and the total economic loss in an earthquake event have received much attention. These include the development of sustainable and high-performance materials, innovative structural configurations, and effective earthquake protection technologies. There also exists tremendous potential to transform the construction process of building and other infrastructure types using modern fabrication technologies. For example, borrowed from the field of rapid prototyping, it is now possible to use 3-dimensional printing together with sustainable rapid-set cementitious materials to accelerate the construction process. System-level testing provides the ultimate evaluation of these concepts, which can lead to new breakthroughs in structural engineering and earthquake hazard protection.
- ***What are the impacts of nonstructural components on overall losses in earthquakes and how can such loss be minimized?*** Damage to architectural elements, mechanical/electrical/plumbing systems, and building contents, often collectively referred to as nonstructural components and systems (NCSs), can incur significant direct and indirect economic losses in the event of an earthquake. Repair and

replacement costs can be significant and the temporary loss of functionality of critical facilities like hospitals is not only costly but also has direct and indirect impacts on life safety. Moreover, to support safe evacuation and post-event rescue, it is absolutely essential that some of these systems, such as those supporting egress, remain operable following an earthquake. This has become an important consideration in the next-generation PBD methodology. Understanding how non-structural components respond and interact with the structural system and devising effective means to protect them from damage are essential. This requires system-level studies with realistic structures and realistic earthquake excitation on total structural systems (structures that house NCSs). Data from these studies can be used to derive fragility functions for PBD.

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