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NEES RESEARCH HIGHLIGHTS: 2004-2009

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ABSTRACT

During the first five years of research at the fifteen NEES experimental sites, almost 130 multi-year, multi-investigator projects have been completed or are in progress. This number includes those funded by NSF through the NEESR Program and those funded by other agencies under the NEES Shared-Use Program (Non-NEESR). The common theme in all of these projects has been the use of cutting-edge experimental simulation tools and facilities to reduce earthquake risk. Whereas experimental work has been undertaken in the past, the distinguishing feature of most of these studies is that they have been conducted at large scale to better replicate nonlinear behavior and simulate collapse. Studies have ranged from improving the seismic performance of steel and concrete structures to understanding geotechnical response (using shake tables, floor-mounted actuator assemblies, centrifuges, and field equipment), and from understanding site behavior to mitigating tsunamis (using instrumented field sites and wave basins). Many advances in earthquake engineering have been made during this time and some examples are presented in this paper.

Introduction

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) was established by the National Science Foundation in 2004 to conduct cutting-edge research in earthquake risk mitigation. The purpose of this paper is to provide an understanding of the breadth of research projects that have been undertaken in the NEES Program in the last five years. Since many of the 130 projects that have been funded in this Program are multi-year, multi-institutional projects, only a small number have actually been completed at this time. Thus much of the work described in this paper is work-in-progress. Furthermore, the projects highlighted herein were chosen to represent the breadth of activity and it is readily admitted that not every notable project has been included. Many worthy candidates were excluded for reasons of limited space. Information about these projects and more detail about those reported in this paper, are available from NEEScomm (2010). It is also noted that highlights in Information Technology, and Education, Outreach and Training, were considered to be outside the scope of this paper.

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Selected Research Highlights

This paper summarizes nine research highlights involving 13 NEES equipment sites. The first seven describe new discoveries in earthquake engineering and advances in seismic safety, and the last two are examples of breakthroughs in experimental simulation.

NEESWood: Development of a Performance-Based Seismic Design Philosophy for Mid-Rise Woodframe Construction (Van de Lindt, 2005)

Figure 1a. Testing a two-story, full scale, woodframe condominium on the NEES shake tables at the University at Buffalo.

The objective of the NEESWood project is to develop a performance-based seismic design (PBSD) philosophy to safely increase the height of woodframe structures in active seismic zones of the U. S. as well as mitigate damage to low-rise woodframe structures. During the first year, full-scale seismic benchmark tests of a two-story woodframe townhouse were performed using the two, NEES shake tables at the University at Buffalo (Figure 1a). As the largest full-scale, three-dimensional shake table test performed in the United States at the time, the test results served as a benchmark for both woodframe performance and nonlinear models for seismic analysis of woodframe structures.

Figure 1b. Testing the capstone building on the E-defense shake table near Kobe, Japan.

These experiments culminated in a Capstone Test Program conducted at the National Research Institute for Earth Science and Disaster Prevention (NIED) E-Defense shake table facility in Japan under a Memorandum of Understanding between NEES and NIED. The Program consisted of two phases. The Phase I test specimen was a seven-story, 40-ft by 60-ft condominium tower with 23 one- and two-bedroom living units and space formed by a steel frame at level 1 to accommodate two retail shops (Figure 1b). For Phase II, the steel moment frame was locked down to become an extension of the shake table and only the six-stories of light-frame wood were tested. The Phase II building was subjected to a small earthquake, a design-basis earthquake, and the maximum considered earthquake (MCE) for the city of Los Angeles, with a return period of 2500 years. The building had no structural damage following the MCE test and its performance successfully validated the design philosophy developed by the NEESWood project.

The project team is now working with the Wood Technical Support Committee (BSSC TS7) to help codify the design of mid-rise woodframe buildings. The NEESWood team has also provided numerical simulation support to the Canadian government to help validate the inclusion of six-story mid-rise woodframe buildings in the Canadian National Building Code.

Development of a Seismic Design Methodology for Precast Floor Diaphragms (Fleischman, 2003)

The development of a seismic design methodology for precast concrete floor diaphragms is complicated by the fact that the seismic force levels developed in the diaphragms depend on the dynamic interaction between the diaphragms and the primary lateral force-resisting elements (e.g., shear walls and moment resisting frames), which in turn depends on the elastic and inelastic behavior of both the diaphragms and the lateral-force resisting systems. Furthermore, the inelastic behavior of precast diaphragms, including the internal force-resisting mechanisms, and the deformation demands and capacities of critical elements, is complex and poorly understood because of the jointed nature of these diaphragms.

Figure 2. Testing a three-story, half-scale precast concrete parking garage on the NEES shake table at University of California San Diego.

To provide insight into this behavior, a half-scale model of a three-story precast parking structure was tested at the Englekirk Structural Engineering Center at the University of San Diego, using the NEES outdoor shake table. Weighing almost one-million pounds, the structure is the largest such specimen tested in the U.S. to date (Figure 2). It was subjected to a series of simulated events representing earthquakes that have occurred in Knoxville, Seattle, and Northridge. The results from these experiments are being used to develop a robust design methodology for these structures which in turn will lead to the increased use of this popular and economical form of construction in seismically active regions. The design, instrumentation, and testing of this one-half-scale structure involved extensive collaboration between UC San Diego, the University of Arizona, Lehigh University and the Precast/Prestressed Concrete Institute.

Mitigation of Collapse Risk in Vulnerable Concrete Buildings (Moehle, 2006)

The objective of this NEESR Grand Challenge project is to study the collapse potential of older nonductile concrete buildings to improve assessment and retrofit tools, and to define appropriate incentives or policy measures to mitigate the risk. Four areas are being researched: 1) exposure (inventory), 2) component and system performance, 3) building and regional simulation, and 4) mitigation strategies. The project involves multiple NEES equipment sites and several partner institutions: columns are being tested at the University of Minnesota facility, full-scale beam-column joints under high axial loads at the University of California, Berkeley site, and soil-structure interaction studies on shear-wall frame substructures at one of the University

California, Santa Barbara field sites using the UCLA mobile lab. The project is using the city of Los Angeles as a testbed for the simulation studies and inventory collection to evaluate the tools developed from the experimental program. Collaborators include researchers at UC Berkeley, Purdue University, the University of Kansas, San José State University, UC San Diego, University Puerto Rico, Mayaguez, UCLA, and the University of Washington. The team is also working closely with the Concrete Coalition from EERI as a partner in the inventory studies and outreach to the profession.

Axial failure of the columns of a non ductile building is one of the primary causes of collapse during an earthquake. Giving engineers the tools to identify these columns is a strategic goal of this project. Researchers from the University of Kansas and Purdue University conducted experiments at the large-scale NEES facility at the University of Minnesota in which nonductile reinforced concrete column specimens were subjected to displacement cycles, similar to those caused by earthquakes until the columns experienced axial failure (Figure 3). It was found that the maximum deformation sustained before collapse was strongly influenced by the displacement history imposed on the columns. Test results are providing new knowledge, which is helping to understand how columns fail during earthquakes, and will be key to the improvement of seismic rehabilitation standards such as ASCE-41.

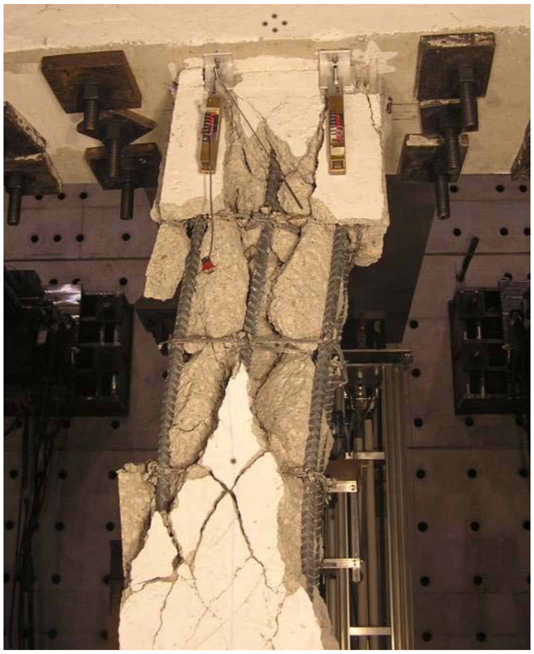

Figure 3. Nonductile concrete column tested to axial failure at the NEES facility at University of Minnesota.

The NEES facility at the University of Minnesota has the capability of subjecting a structural component to displacements in all six degrees-of-freedom. This ability allows researchers to subject column specimens to bi-directional displacement test protocols that more accurately reflect conditions experienced during earthquakes. This is the first time that a comprehensive testing program of this nature has been conducted to study the vulnerability of columns to collapse.

Controlled Rocking of Steel-Framed Buildings with Replaceable Energy Dissipating Fuses (Deierlein, 2005)

Experience from past earthquakes suggests the need for buildings that are less vulnerable to damage and easier to repair after a major earthquake. The self-righting rocking frame system studied in this project is designed based on performance-based engineering concepts to minimize, and potentially eliminate, damage to steel braced frame systems for buildings. This is in contrast to conventional steel braced-frame systems, where it is accepted that costly damage, including buckling and fracture of structural members, is likely to occur under severe earthquakes. The newly proposed system prevents such damage through the mechanism of controlled rocking, whereby the building frame columns are permitted to rock and shield the frame members from excessive forces. Specially configured steel fuses are employed to dissipate earthquake-induced energy and damp out the rocking vibrations. Designed as replaceable elements, the fuses facilitate rapid repair that may be necessary after extreme earthquakes.

Through a combined program of computational and experimental research, the project includes simulation of component and system response, and synthesis of the results through a methodology for performance-based design that directly assesses life safety and life-cycle economic factors. The proposed concept emphasizes damage prevention to foundations and other structural elements that are difficult to repair; inelastic energy dissipation in structural fuses that are easy to replace; story drift control so that nonstructural damage is reduced; and sufficient safety against collapse.

Figure 4. Testing the performance of a damage-tolerant rocking steel frame on the E-Defense shake table near Kobe, Japan.

One important phase of the experimental work was the shake table testing of a three-story steel braced frame that incorporated high-strength post-tensioning tendons and replaceable energy dissipating fuses to resist earthquake effects. The tests were conducted at the NIED E-Defense shake table facility in Japan under the NEES/NIED Memorandum of Understanding (Figure 4). Data from the tests have been used to validate the nonlinear computer models that are used to generalize the results to other building configurations. The shake table tests were the culmination of three years of research and development to devise the rocking frame system along with its specially designed butterfly shaped fuses, post-tensioning anchorages, rocking column bases, and other framing details. The dynamic shake table tests were preceded by quasi-static and pseudo-dynamic testing of large-scale framing subassemblies at the NEES facility at the University of Illinois and fuse tests conducted at Stanford University. In addition to researchers at Stanford University and the University of Illinois, the research team included professional structural engineers from California and researchers from the Tokyo Institute of Technology, Hokkaido University, Kyoto University, and the National Research Institute for Earth Science and Disaster Prevention (NIED).

Seismic Performance of Bridge Systems with Conventional and Innovative Materials (Saiidi, 2004)

The objective of this project is to make a significant improvement in the seismic performance of highway bridges using innovative materials. Traditionally bridges are designed to a ‘no-collapse’ criterion particularly in high seismic zones. This means that whereas life-safety is preserved in a major earthquake, the bridge may be heavily damaged and may need to be replaced, causing significant disruption to service. In this project, improved functionality is the goal and large-scale experiments on three, four-span bridges have been conducted to investigate the feasibility of this objective. Using three of the four NEES shake tables at the University of Nevada Reno, and two abutments equipped with servo-hydraulic actuators, three, quarter-scale models were tested (Figure 5).

Figure 5. Testing a four-span, quarter scale, bridge on the NEES shake tables at the University of Nevada Reno.

Whereas the first bridge model was a conventional reinforced concrete structure approximately 110 feet long, the next two incorporated innovative seismic-resistant features. These included reinforced concrete piers with outer layers made from fiber-reinforced concrete polymer composites and built-in isolators designed to absorb and reduce seismic forces and column-footing connections toughened with superelastic nickel titanium rods and "bendable concrete." All models were subjected to the same set of progressively increasing ground motions until collapse was imminent. Preliminary results indicate superior behavior of the latter two models compared to the first, with minimal residual displacement and only light damage to the columns even under the most intense motions. Other collaborators in this project include researchers from University of California San Diego, Florida International University, and the Tokyo Institute of Technology.

Seismic Risk Mitigation for Port Systems (Rix, 2005)

Seismic risks faced by ports are unique due to the nature of their infrastructure, long-range planning horizon, diversity of stakeholders, and the roles of port authorities. Understanding the complex soil-foundation-structure systems typical of ports, and development of geotechnical and structural mitigation strategies, are key to reducing this risk. One of the aspects of this Grand Challenge project is the mitigation of damage to container cranes when subject to large ground deformation caused by liquefaction. Past earthquakes have highlighted the vulnerability of container cranes to damage from even moderate earthquakes, and despite their importance to the continuing functionality of ports, this is the first time their seismic performance has been studied in the United States.

To better understand how container cranes respond during an earthquake, two subscale crane test specimens were developed and tested on the NEES shake tables at the

Figure 6. Testing of a 1/20th scale model of a container crane on one of the NEES shake tables at the University at Buffalo.

University at Buffalo. The first was a 1/20th-scale structure that was used to investigate the elastic and uplift behavior of these cranes (Figure 6). Uplift at a peak ground acceleration of 0.35g was encountered and the response of the structure was dominated by the behavior of its lower portion.

These results were used to develop the second experimental test program, which included the design and construction of a 1/10th-scale model of a container crane. The objective of these tests was to measure the response of the crane from small levels of shaking to those large enough to cause it to collapse. The data collected from these tests provided information on the likelihood of different types of damage as a function of the level of shaking, allowing computer models of cranes to be developed and verified. When damage to the test crane occurred, repairs similar to those used in the field were made. The repaired crane was tested again to determine how well the repairs performed during subsequent seismic events. These tests were the largest ever performed in the U.S. and the first to include collapse.

The results of this comprehensive series of large-scale tests will be used to assess the expected performance of existing container cranes and, if necessary, design retrofit measures to reduce the possibility of damage during earthquakes. The test results will also be used to develop improved design standards for future cranes.

This project is being led by researchers at Georgia Institute of Technology. Other collaborators include researchers from University of Texas at Austin, University of California-Davis, University of Washington, MIT, University of Illinois-Urbana-Champaign, Drexel University, and several practicing engineers.

Development of Performance Based Tsunami Engineering (Riggs, 2005)

The current lack of design guidance for tsunami loading exposes coastal communities in the U.S. and around the world to potentially catastrophic consequences of tsunami inundation. While the development of warning systems and educational programs has come a long way since the 2004 Indian Ocean tsunami, there is still a marked lack of design guidelines and tools that accurately simulate tsunami run-up and loading on coastal infrastructure.

Figure 7. Experimental tsunami bore impacting instrumented wall specimen in NEES Large Wave Flume at Oregon State University.

In this four-year project, researchers have performed numerous wave run-up and loading experiments using the NEES facilities in the O.H. Hinsdale Wave Laboratory at Oregon State University (Figure 7). The experiments have been designed to validate computer simulation models for tsunami bore development and coastal inundation, sediment transport and scour, and loading on coastal structures. Experiments have been performed at two different scales in order to verify the extrapolation of both the simulation tools and empirical design expressions to real world scale. Two-dimensional flumes were constructed in the NEES Tsunami Wave Basin at OSU where solitary waves up to 24 in (60 cm) height could be generated. This resulted in tsunami bores up to 10 in (25 cm) in height at the structural test models. The piston-style wave maker in the Large Wave Flume was used to generate solitary waves up to 51 in (130 cm) height, resulting in bores up to 20 in (50 cm) in height at the structural models.

It is expected that measurements of tsunami bore loadings on individual structural components such as columns, walls and floor slabs will lead to the development of loading expressions for use in structural design of coastal structures. Results will be developed in code compatible language to ease adoption by national and local code adoption agencies.

This project is being led by researchers from the University of Hawaii at Manoa. Other collaborators include researchers at Oregon State University and Princeton University.

Advances in Hybrid Simulation

Notable advances in hybrid simulation have been made at several NEES Equipment Sites in the last five years. These include advanced software tools which greatly simplify the task of running a distributed hybrid simulation such as OpenFresco from the University of California Berkeley, and SIMCOR from the University of Illinois Urbana-Champaign. Other developments are combinations of software and high performing actuators which bring real-time (fast) hybrid simulation within reach.

Real-time hybrid simulation combines physical testing and numerical simulation such that the dynamic performance of the entire structural system can be considered during the simulation. For example when real-time hybrid simulation is used to evaluate the performance of a structure with rate-dependent damping devices, the devices are tested as experimental substructures while the rest of the structure is modeled analytically (Figure 8). The added benefit of this technique is that it enables a large number of ground motions to be applied of increasing severity without the need to repair the test specimens since the damage that does occur does so within the analytical substructure (Ricles et al., 2010). Sites that have developed this capability include the RTMD facility (Real-Time Multi-Directional Facility) at Lehigh University, and the CU-NEES facility at the University of Colorado, Boulder.

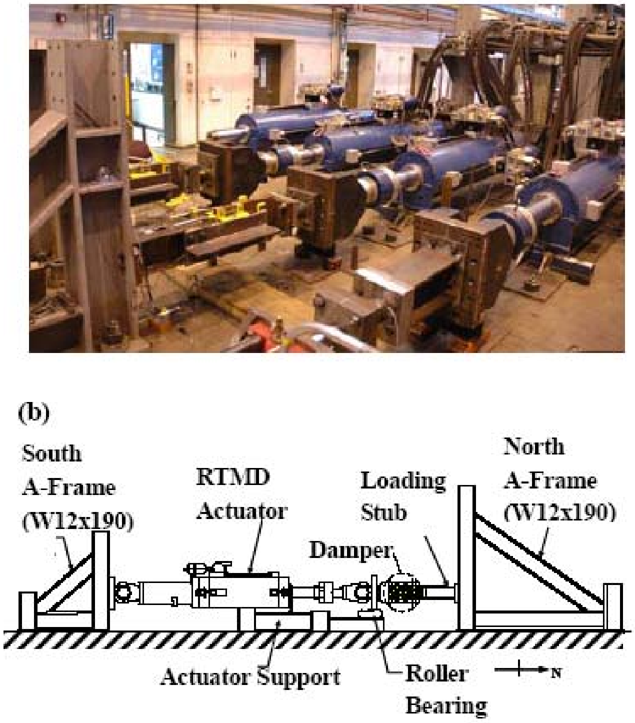

Figure 8. RTMD testing of a building with elastomeric dampers at Lehigh University.

Advanced Site Monitoring and Effective Characterization of Site Nonlinear Dynamic Properties and Model Calibration (Zeghal, 2008)

The objective of this research program is to develop a capability to monitor the cyclic and permanent displacement of field sites, and to use the associated measurements to characterize the in situ properties of soil strata to a depth of about 30 meters. For this purpose a number of wireless shape-acceleration arrays (WSSA) are being installed permanently at the NEES Wildlife liquefaction site operated by UC Santa Barbara to monitor low strain response as well as earthquake induced liquefaction, permanent deformation and lateral spreading. In the event of an earthquake, it is expected that the installed arrays will provide, for the first time, measurement of the time history of a site lateral spreading profile.

But this technology/monitoring development also has application to other natural and man-made hazards such as slope stability, urban site dynamic response during construction, and real-time monitoring of dam and levees. The SSA is currently being used by two NEES facilities (University of Buffalo, UC Santa Barbara), E-Defense, as well as several Departments of Transportation (DOTs) and construction companies. For example, the Minnesota DOT (Mn/DOT) recently used the SAA to monitor an active soil system near a busy highway. The SAA helped the DOT predict an impending failure 48 hours in advance allowing the highway to be closed just before the highway collapsed (Figure 9). SAA is also the centerpiece of a NIST project on the development of a multi-scale monitoring and health assessment framework for the management of levees and flood-control systems.

Figure 9. Slope failure on a Minnesota highway that was successfully predicted using Wireless Shape-Acceleration Arrays (Photo courtesy Mn/DOT).

Conclusions

During the first five years of research at the 15 NEES experimental sites, almost 130 multi-year, multi-investigator projects have been completed or are in progress. The common theme in all of these projects has been the use of cutting-edge experimental simulation tools and facilities to reduce earthquake risk. Whereas experimental work has been undertaken in the past, the distinguishing feature of most of these studies is that they have been conducted at large scale to better replicate nonlinear behavior and simulate collapse. Studies have ranged from improving the seismic performance of wood, steel and concrete structures to understanding site behavior and mitigating the consequences of tsunamis. While advances in earthquake engineering have been made during this time, only some examples have been presented in this paper.

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References

ASCE 41-06. 2007. *Seismic Rehabilitation of Existing Buildings*, American Society of Civil Engineers, New York.

Deierlein, G., 2005. *Controlled Rocking of Steel-Framed Buildings with Replaceable Energy Dissipating Fuses*, Stanford University, National Science Foundation Award NEESR-SG: 0530756.

Fleischman, R., 2003. *Development of a Seismic Design Methodology for Precast Floor Diaphragms*, University of Arizona, National Science Foundation Award Pre-NEESR: 0324522.

Moehle, J., 2006. *Mitigation of Collapse Risk in Vulnerable Concrete Buildings*, University of California Berkeley, National Science Foundation Award NEESR-GC: 0618804.

NEEScomm, 2010. *NEES Facility Project Highlights*, NEEScomm, Purdue University, Lafayette, IN.

Ricles, J. M., Sause, R., Karavasislis, T. L., and Chen, C., 2010. *Performance-Based Seismic Design of Building Systems with Dampers: Experimental Validation Using Real-Time Hybrid Simulation,* Joint Conf. Proc. 7CUEE and 5ICEE, Tokyo Institute of Technology, Tokyo.

Riggs, H. R., 2005. *Development of Performance Based Tsunami Engineering, PBTE*, University of Hawaii, National Science Foundation Award NEESR-SG: 0530759.

Rix, G., 2005. *Seismic Risk Mitigation for Port Systems*, Georgia Inst. Technology, National Science Foundation Award NEESR-GC: 0530478.

Saiidi, M., 2004. *Seismic Performance of Bridge Systems with Conventional and Innovative Materials*, University of Nevada Reno, National Science Foundation Award NEESR-SG: CMMI 0420347.

Van de Lindt, J., 2005. *NEESWood: Development of a Performance-Based Seismic Design Philosophy for Mid-Rise Woodframe Construction*, Colorado State University, National Science Foundation Award NEESR-SG: CMMI 0529903.

Zeghal, M., 2008. *Advanced Site Monitoring and Effective Characterization of Site Nonlinear Dynamic Properties and Model Calibration*, Rensselaer Polytechnic Institute, National Science Foundation Award NEESR-II: 083032.