The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES): A Resource for Structural Engineers

Julio Ramirez, Center Director
Thalia Anagnos, co-Leader Education, Outreach, and Training
Rudolf Eigenmann, co-Leader Information Technology
NEEScomm
Discovery Park, Purdue University
West Lafayette, IN

Abstract

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) is a network of 14 advanced experimental sites connected by an advanced cyberinfrastructure that enables the operation and control of interconnected multi-site experiments, remote viewing and participation, rapid data viewing and analysis, and data archiving. During the first six years of research at the NEES experimental sites, over 160 multi-year, multi-investigator projects have been completed or are in progress, yielding many advances in earthquake engineering. The results of NEES research are of great interest to the structural engineering profession as they potentially inform and promote code changes as well as advances in design and construction practices.

A robust and user-requirements driven cyberinfrastructure and its tools are making it possible to provide practitioners with access to the rich data sets, models, and videos that are produced by the research community, as well as resources for guided or self-paced learning. In October 2009, staff at NEEScomm, the NEES Operations headquartered at Discovery Park in Purdue University, began building a new cyberinfrastructure on the HUBzero platform, which has proven successful in the area of nanotechnology. This cyberinfrastructure, called NEEShub, released in July 2010, provides convenient access to the NEES data repository, referred to as the *Project Warehouse*, and hosts a range of tools for data visualization, analysis, and computational simulation. The NEES Academy, also under development on the NEEShub platform, is designed to host a rich set of resources aimed at disseminating new earthquake engineering knowledge to the profession as well as educating the next generation of researchers and practitioners. Here we provide brief descriptions and examples of the many benefits accrued to the practice community through the research, outreach, information technology, and educational activities of NEES.

Introduction

On September 30, 1994 the U.S. Senate passed Public Law 103-374 authorizing appropriations for carrying out the Earthquake Hazards Reduction Act of 1977 for fiscal years 1995 and 1996. Section 2 of the Senate bill described the need for a national assessment of earthquake engineering research and test facilities. The Senate bill was approved by the House of Representatives on October 5, 1994 and was signed by President Clinton on October 19, 1994. In response to this directive, the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST) awarded a grant to the Earthquake Engineering Research Institute (EERI) to conduct this assessment. The findings from the EERI study, *Assessment of Earthquake Engineering Research and Testing Capabilities in the United States* (1995) jump-started the development and commissioning of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES), culminating more than a decade of planning and intense work by the earthquake engineering community.

In November 1998, the National Science Board approved NEES for construction with funds totaling $82 million from the NSF Major Research Equipment and Facilities Construction (MREFC) appropriation. Construction occurred during the period 2000-2004, resulting in the current network of 14 advanced experimental sites connected by an advanced cyberinfrastructure that enables the operation and control of interconnected multi-site experiments, remote viewing and participation, rapid data viewing and analysis, and data archiving. NEES began operation on October 1, 2004 under the management of NEESinc. On October 1, 2009, NSF and Purdue University entered into a five-year Cooperative Agreement to transfer NEES operations to NEEScomm (NEES Community and Communication).

During the first six years of research at the NEES experimental sites, over 160 multi-year, multi-investigator

projects have been completed or are in progress. This number includes those funded by NSF through the NEES Research Program (NEESR) and those funded by other agencies under the NEES Shared-Use Program (Non-NEESR). Today, NEES is a major national resource, meeting the research needs of the earthquake engineering community and contributing many advances to the state of the practice. This NSF-funded network of structural, geotechnical, tsunami and earth science fixed and mobile laboratories provides a fertile environment for collaboration to tackle major earthquake engineering challenges in a multidisciplinary fashion. With the current 14 NEES facilities and the network cyberinfrastructure, researchers have the capability to conduct a variety of large-scale physical simulations and relatively simple hybrid simulations. These facilities are making it possible for researchers to perform a new generation of experiments and do so in an environment that encourages and supports collaboration. The cyber-infrastructure of the NEES collaboratory also allows the research, professional, and education communities to ingest, store, and access data that are useful for informing future research and engineering practice developments, as well as supporting students to better understand underlying theory.

Whereas significant earthquake engineering experimental work has been undertaken in the past, the distinguishing feature of NEES studies is that they have been conducted at large scale to better replicate nonlinear behavior and simulate collapse. These studies often involve multiple sites and multiple investigators representing universities and companies from around the country and around the world (Buckle and Ramirez, 2010; Ramirez, 2010). 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 the following section.

NEES research has greatly benefited from partnerships with the professional community. To date, many practitioners have participated in NEES research, and a number of projects have been sponsored by companies, utilities, and non-profits to test prototypes of innovations in seismic-resistant design. Collaborations with professional organizations such as EERI, ATC, SEAOC, and ACI as well as government agencies such as NIST and FEMA promise to accelerate dissemination and implementation of important research findings.

NEES Research – Understanding and Improving Seismic Performance

The focus of this section is to provide a sample of the breadth of research projects that have been undertaken in the NEES Program using the network of diverse experimental sites. Several of these projects have been conducted in close partnership with practitioners and professional associations. The projects highlighted in this section illustrate the breadth of research activity but regrettably many notable projects were excluded because of limited space. More information about these projects and others can be found in Buckle and Ramirez (2010), in the 2009-2010 NEES Highlights (NEEScomm, 2010) and in the NEES Project Warehouse. Since many of the 160 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 section is work-in-progress. The five projects described in this section involve eight NEES equipment sites and one international partner facility in Japan as well as multiple industry and professional collaborators. They yield new discoveries in earthquake engineering and advances in seismic safety.

NEESWood: Development of a Performance-Based Seismic Design Philosophy for Mid-Rise Woodframe Construction (Van de Lindt, NSF CMMI-0529903, 2005)

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. In 2006, full-scale seismic benchmark tests of a two-story woodframe townhouse were performed using the two NEES shake tables at the University at Buffalo. 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.

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 retail shops (Figure 1). 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.

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

The project team is now working with the BSSC 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, NSF CMMI-0324522, 2004)

The objective of this project is to develop a comprehensive, accurate, and efficient design methodology for precast concrete floor diaphragms in buildings subjected to seismic loading. 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). This dynamic interaction, 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 deformation demands, is complex and poorly understood because of the jointed nature of these diaphragms.

To provide insight into this complex floor diaphragm behavior, a half-scale model of a three-story precast parking structure was tested at the Englekirk Structural Engineering Center at the University of California San Diego, using the NEES Large High-Performance Outdoor Shake Table (LHPOST), the largest outdoor shake table in the world. 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.

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

Mitigation of Collapse Risk in Vulnerable Concrete Buildings (Moehle, NSF CMMI 0618804, 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. The research plan includes four areas of study: 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 were 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, UC San

Diego, UCLA, Purdue University, the University of Kansas, San José State University, University of Puerto Rico, Mayaguez, and the University of Washington.

The team is also working closely with the Concrete Coalition as a partner in the inventory studies and outreach to the profession. The Concrete Coalition, a joint project of the Earthquake Engineering Research Institute (EERI), the Applied Technology Council (ATC) and the Pacific Earthquake Engineering Center (PEER) at UC Berkeley, and their partners, including the Structural Engineering Association of California, the American Concrete Institute, Building Owners and Managers (BOMA) of Greater Los Angeles and the U.S. Geological Survey. It is a network of individuals, governments, institutions and agencies with an interest in assessing the risks associated with concrete buildings and fixing them if the risk is too high. Concrete Coalition members from throughout the state of California have developed inventories of pre-1980 buildings from more than 20 cities.

Axial failure of the columns of a nonductile 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. 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.

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. To facilitate the transfer of this research to practice, the National Institute for Standards and Technology (NIST) has initiated a two-phase project, NIST Task Order 5 (ATC-76-5) with the primary objective being the development of nationally accepted guidelines for the collapse prevention of nonductile reinforced concrete buildings.

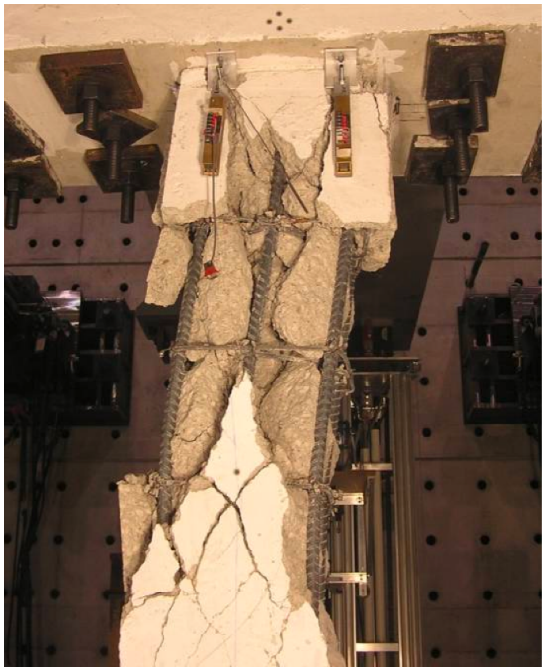

Figure 3. Nonductile concrete column tested to axial failure at the NEES facility at University of Minnesota.

Shared Use and Service-to-Industry Projects

The NEES laboratories also carry out research to support industry and nonprofits in testing of prototypes and innovative new designs. The term "shared-use" denotes use of a NEES Equipment Site facility under MOM-supported (Management, Operations and Maintenance) recharge rates to conduct research funded by programs other than the NSF NEES research program. The goal is to make NEES facilities available to partner public-interest research organizations for shared-use research and public data archive as a means to maximize the NSF and taxpayer investment in the NEES infrastructure.

One such project, funded by the Earthquake Engineering Research Institute Endowment Fund, involved testing a full-scale straw bale house under consideration by the Pakistan Straw Bale and Appropriate Building (PAKSBAB) organization as an alternative to the typical highly-vulnerable brick or masonry block construction found in northern Pakistan. More information on PAKSBAB is found at www.paksbab.org. The 14 ft x 14 ft x 10 ft straw bale house shown in Figure 4 was subjected to accelerations up to 0.82g, and though it did show cracking, it did not collapse. This experimental study showed that this low-cost residential construction performs much better than the typical housing that exhibited a high rate of collapse in the October 2005 Kashmir earthquake that killed close to 80,000 people.

Figure 4. Straw bale house tested at University of Nevada, Reno, did not collapse after extreme loading.

The NEES at Cornell University site tested an innovative pipeline concept for the San Francisco Public Utilities Commission. The test program was developed as a proof of concept for a major seismic upgrade to the large diameter water supply pipeline that crosses the Hayward Fault. The prototype pipeline segments, tested at 1/10 scale, withstood both lateral offset and compressive deformation. The resulting data allowed researchers to validate the design concept, as well as examine the mechanical behavior of the pipeline joints and the soil-structure interaction

Figure 5. Water supply pipeline system tested in the Large-Scale Lifelines Testing Facility at Cornell University accommodated fault offset.

NEEShub – Cyberinfrastructure for Supporting Research and Dissemination

The NEES cyberinfrastructure serves as a collaboration platform for equipment sites, researchers, students, educators and professionals. The NEEShub, released in July 2010, provides convenient access to the NEES data repository, referred to as the Project Warehouse, and hosts a range of tools for data visualization, analysis, and computational simulation, the large majority of which are contributed by the researchers. Tools can be invoked directly at the nees.org web site, without the need for software download and installation. The NEES Academy, being developed on the NEEShub platform, will host a rich set of community developed resources aimed at disseminating new earthquake engineering knowledge to the profession as well as educating the next generation of researchers and practitioners. NEEShub development aims to provide researchers, educators, and practitioners the tools and collaboration environment needed to accelerate the mitigation of earthquake and tsunami risk. The resulting engaged community produces a network that is more powerful than the sum of its parts, where researchers and educators can contribute and collaborate in ways previously not possible, thus becoming a model for research programs in other hazards.

NEEShub: At the top of NEEScomm's priority list for the development of the cyberinfrastructure is the *NEEShub*, which will bring advanced functionality to the NEES web portal at nees.org. The cyberinfrastructure development team, working with the earthquake community, chose an underlying HUB platform that has proven successful in the science domain of nanotechnology with over 90,000 users (McLennan and Kennell, 2010). This platform allows the execution of tools over the World Wide Web and the sharing of information. On NEEShub, NEES data are collocated with their analysis and visualization tools. That is, the actual tool execution platform is physically close to the data repository, allowing for fast data transfer. Thus, users will be able to inspect large data volumes without incurring excessive data transfer times. Launching simulation tools, such as OpenSees, on the NEEShub can also take advantage of the platform's connection to powerful high-performance computing resources. This means that an engineer launching a computational simulation job on NEEShub can request that the job be executed on one of the National Science Foundation's TeraGrid platforms. While the NEEShub's ability to execute software tools online, without download and installation, adds convenience and reduces data transfers, some users may prefer to install tools on their local machines; conventional download of both software tools and data also will be supported.

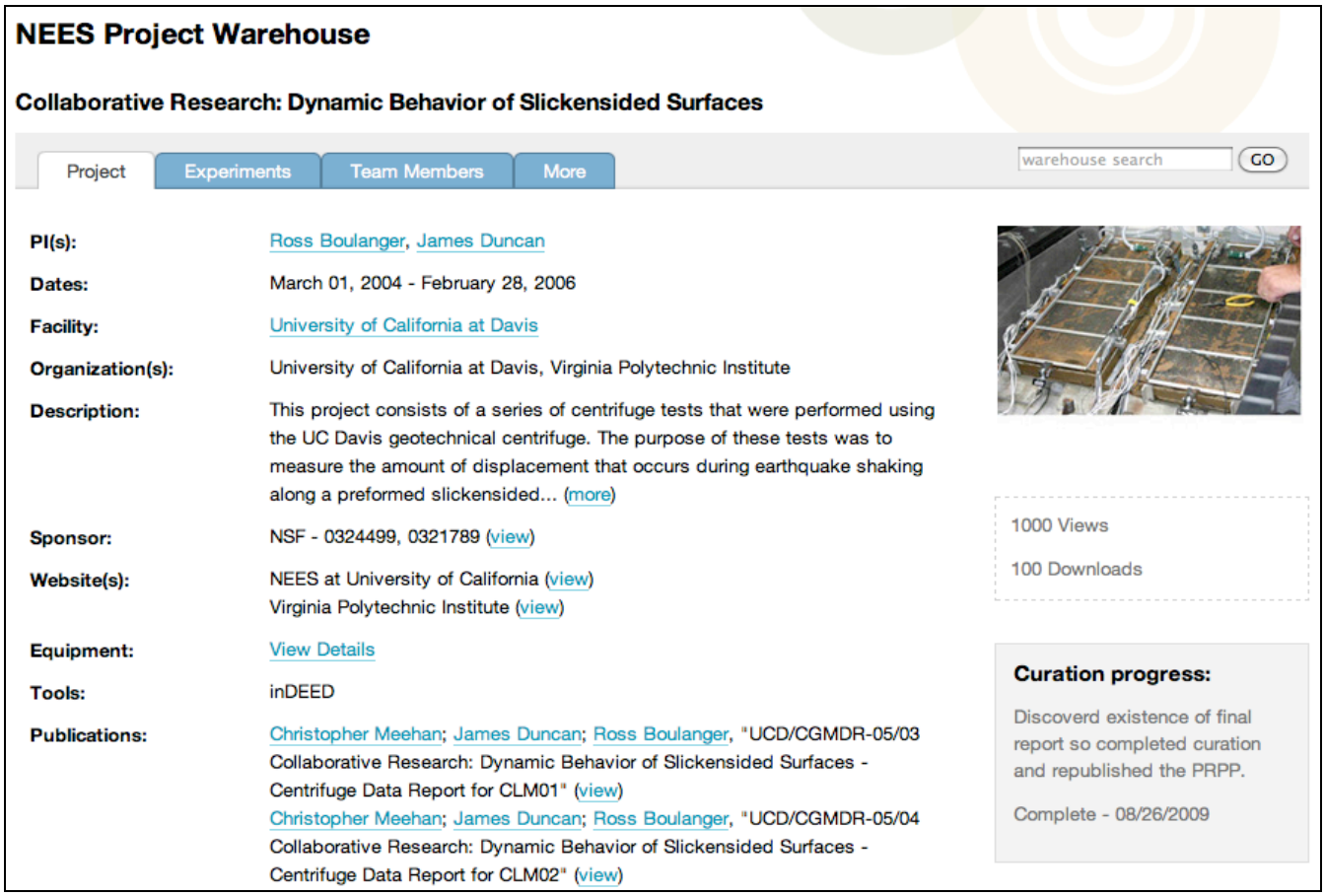

Figure 6: Project Display of a research project in the NEES Project Warehouse

NEES Project Warehouse: The management of research data from analysis and experiments, including data gathering, viewing, and re-use is emerging as a central need in an ever-growing number of science and engineering domains. Because of continuously improving sensor equipment, researchers are able to instrument for a wide range of research needs, collecting vast amounts of information that can be preserved for future studies and the historical record. For example, a specimen may be equipped with hundreds of sensors and dozens of cameras to document its performance when tested on a shake table. The data collected are used by the researcher to evaluate the structural behavior with the final goal of developing recommendations for improved design guidelines and code provisions.

In addition to the immediate use of the collected data by researchers, the information is of value to other scientists and practitioners, who by analyzing archived data can gain new insights, thus enhancing the value of the network to the community. For example, archived NEES test data could be valuable to practitioners for informing performance-based design by providing the information needed to specify component behavior in a nonlinear analysis. The NEES Project Warehouse could also be used to house and make available to practitioners data on structural and nonstructural component characteristics and fragilities for use in the application of methodologies such as ATC-58 (Applied Technology Council, 2009).

Tools for viewing archived research projects and visualizing the captured data are most important for the end user. NEES' ongoing software developments aim to provide a more convenient user interface than has been available previously in the NEES Central data repository. Figure 6 shows the Project Display. This presentation summarizes the key aspects of an experiment such that end users can readily view data and summary information to decide whether the research study is of value for their particular design and analysis needs.

A key capability within this new environment is visualization and inspection of data directly in the NEES Project Warehouse without the need to download large data sets or install software tools on local computers. Figure 7 shows the

data visualization tool (inDEED) that executes directly on a web browser, interfaces with the Project Warehouse, and allows the viewing of NEES project data. The inDEED data viewer is capable of displaying photos, schematics of sensor locations, and a variety of different data plots.

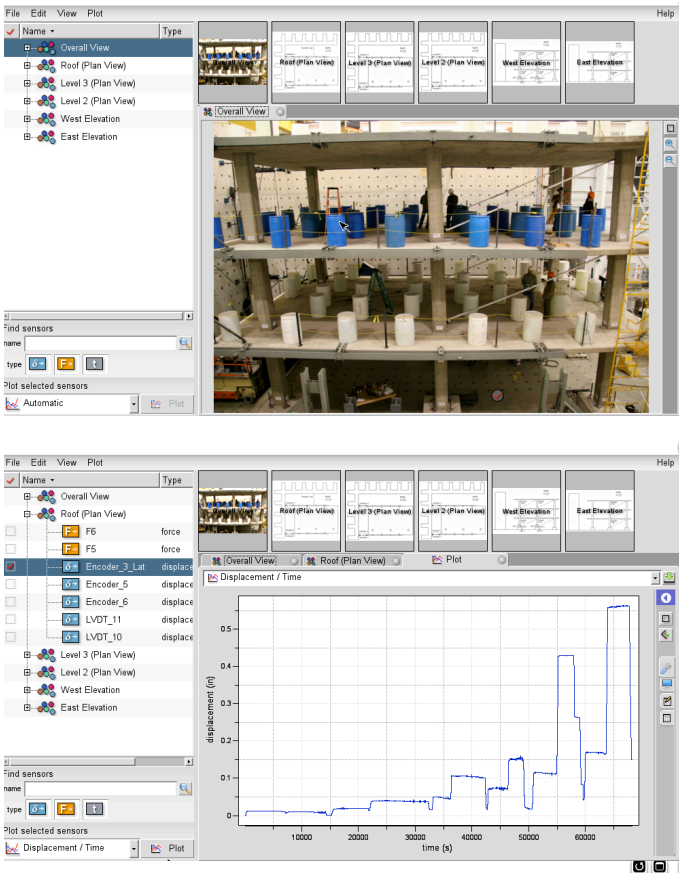

Figure 7. (a) The inDEED tool displaying a photo of the experiment along with schematics of instrument locations. (b) A time history of displacement data for a particular sensor.

Curation at the Source: Data management challenges include data capturing, curation, archiving, and long-term preservation, as well as developing those capabilities so that they support the earthquake engineering community in the best possible way. Archived data are only meaningful if sufficient information is available about the experiments in which the data were captured. Examples are equipment used, specimen dimensions, types and locations of sensors, possible faulty sensors, calibration, drawings and much more. Metadata describe such information. The NEES cyberinfrastructure is moving away from a process in which a Data Curator adds metadata in the archive *after* the researchers have uploaded their results. Instead, *curation at the source* will provide tools through which researchers fully describe the meaning of their experiments and captured data upfront. The key improvement is that the tool allows the incorporation of metadata to the archived information.

Access to Non-NEES Data: Future efforts will include the creation of links within the Project Warehouse to data repositories from non-NEES sources, such as test data gathered in experiments performed at other institutions, ground and building motion records, earthquake and tsunami reconnaissance information, infrastructure inventories, and bridge and smart building monitoring data.

Access to Computational Resources: In summary, the NEEShub hosts a range of software tools that the engineer can use for inspecting and analyzing data and for performing advanced computational simulations. For the latter, the NEEShub will provide access to the resources of powerful high-performance computer systems. While funding models for large computational resources will need to be developed, we envision basic simulation capabilities to be freely available to a broad audience. A variety of inputs will be available to numerical simulations. Simulation capabilities will include open source tools (e.g. OpenSees) as well as commercial tools (e.g. SAP, Abacus, and LS-DYNA). License agreements with these software providers are being negotiated. Users may find free basic access for entry-level simulations and pay-per-use access for larger simulations. All tools will be accompanied by online training material. In addition, the NEEShub further provides a portal to the education, outreach, and training (EOT) activities in the NEES collaboratory, referred to as the NEES Academy.

NEES Education, Outreach, and Training Program

The ultimate success of NEES will be gauged by the extent to which findings from NEES research are incorporated into design and construction practices. Most NEES research projects include industry representatives and practitioners as participants in the experimental and analysis tasks or in an advisory capacity. This type of collaboration ensures that the projects focus on issues that are important in practice, and incorporate typical components and design details in testing protocols. The Concrete Coalition, an outgrowth of the NEES Grand Challenge project on mitigation of collapse risk in older concrete buildings, is an example of researchers working with practitioners through collaboration with the Applied Technology Council (ATC) and Earthquake Engineering Research Institute (EERI) to assess the scope of the problem, provide input throughout the testing phase, and to inform policy makers and the public. However, once the projects are complete, much more outreach and communication needs to be done to transfer findings to the broader community.

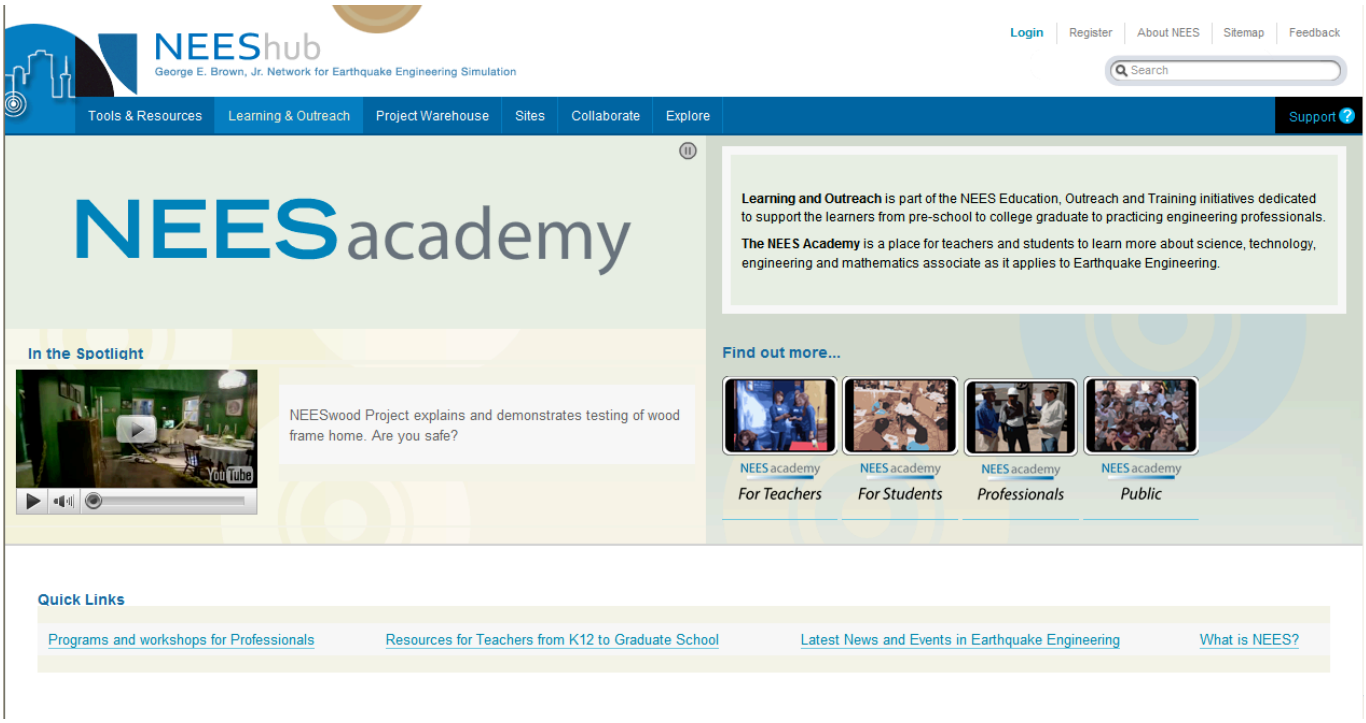

Figure 8: Landing page for the NEES Academy

Having recognized that the most effective technology transfer requires collaboration between the developers and users of technology, NEEScomm is pursuing cooperative programs with various professional organizations to best meet the needs of various stakeholders involved in earthquake risk mitigation, such as architects, engineers, code developers, building officials, and component manufacturers. The first such agreement is with the EERI to deliver an ongoing webinar series entitled *Reducing Earthquake Losses: From Research to Practice*. Each webinar will include both researchers and representatives from relevant areas of practice. The first webinar of the series will highlight seismic design of precast floor diaphragms. Future webinars will focus on outcomes of NEES projects as they come to completion. In addition to conference participation and journal publications, other technology transfer programs under consideration include design guidelines, report series, workshops, and self-contained online informational modules.

NEES must also address training of network users. NEES network research productivity hinges on investigators being proficient with state-of-the-art resources and being able to transfer knowledge fluidly between investigators. Researchers must understand the capabilities and limitations of resources such as large-scale shake tables and wave tanks, advanced sensing equipment and computational models that can interface with this equipment. Access alone is not enough if they want to conduct innovative groundbreaking research. Training will be available to NEES users in multiple formats ranging from one-on-one training by site personnel, to topic–specific workshops, to online modules and videos.

The Education, Outreach, and Training (EOT) program also addresses the learning needs of future earthquake engineers and the general public. As such, the 14 sites and NEEScomm continually work together to develop educational resources to engage K-12 students in activities that teach about how earthquakes affect the built environment. NEES supports a robust research experience for undergraduates (REU) program in which 20 to 30 students each summer spend 10 weeks engaged in research on NEES projects. In addition, NEES is developing the NEES Academy as a centralized resource to collect and disseminate a variety of educational resources aimed at all audiences from kindergarten to practicing professionals.

NEES Academy – A Resource for Education and Outreach

NEES Academy, a virtual formal learning institution, is a portal within NEEShub dedicated to individual learning through online modules and collaborative design with the goal of making research data and research-grade simulations and models accessible to educators and students of all ages. Figure 8 shows the landing page for the NEES Academy. Using the buttons in the middle right section of the window,

different audiences are directed to materials that target their specific needs and questions.

A teacher will find activities and lessons linked to national science standards. A student will find resources to explore questions about earthquakes and their impacts such as videos, interactive simulations, and links to resources developed by related hazard mitigation organizations. A young researcher will find training materials to help him or her effectively use NEES tools in her research. The general public will find information about how NEES is mitigating risk from earthquakes through its research program, and about planned outreach activities at conferences and at equipment sites.

Of particular interest to practitioners, will be continuing education and technology transfer resources. Examples include archived webinars (with potential for earning Continuing Education Units), training on how to use simulation resources, and how to access and review important data from the Project Warehouse. NEES users are encouraged to submit their needs to the NEEShub "wish list" so that efforts can be directed at developing materials that are most important to the community. Additional information on the NEES Academy is found in Anagnos and Brophy (2010).

While the NEES Academy will incorporate materials for all audiences, at least initially, developers will focus on web-based learning materials for target audiences of undergraduate and graduate engineering students, and NEES researchers. As a unifying tool for EOT, the NEES Academy will provide the multiple advantages of disseminating EOT resources to broad audiences, supporting EOT expertise at equipment sites and on NEES research projects, and increasing the potential for consistent and high-quality learning resources for the earthquake engineering community.

Summary

The research and education efforts conducted by the NEES community focusing on mitigation of earthquake and tsunami risk have yielded many advances in earthquake engineering. The results of NEES research are of great interest to the structural engineering profession as they potentially inform and promote code changes as well as advances in design and construction practices. The NEEShub, released in July 2010, provides convenient access to the NEES data repository, referred to as the Project Warehouse, and hosts a range of tools for data visualization, analysis, and computational simulation, the majority of which have been contributed by researchers. The tools can be invoked directly at the nees.org web site without the need for software download and installation. The NEES Academy, also developed on the NEEShub platform, will host a rich set of resources aimed at disseminating new earthquake engineering knowledge to the profession as well as educating the next generation of researchers and practitioners. Expanded collaboration with professional organizations such as SEAOC is essential to accelerating the dissemination and implementation of the important discoveries resulting from NEES research.

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