Teaching Innovation through Hands-on-Experience Case Studies Combined with Hybrid Simulation

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Abstract: Teaching innovations in earthquake engineering with special attention to Bloom's taxonomy is explored utilizing the versatility introduced by the hybrid simulation (HS) testing method. Such innovations focus on developing a variety of case studies with integrated earthquake and structural engineering concepts tailored for high school and first-year undergraduate students. The goal is to effectively guide students to understand the intricacies of real structural systems by visualizing their complex behavior when subjected to earthquake loading. A teaching activity involving theoretical and hands-on-experience components, in which a HS testing demonstration is used as a part of the activity, is described, and the results of this activity are presented. The experiences gathered from this activity and the developed HS experience at various laboratories are used to create new instructional case studies making use of HS. **DOI: 10.1061/(ASCE)EI.1943-5541.0000146.**

CE Database subject headings: Earthquake engineering; Engineering education; Simulation; Case studies; Hybrid methods.

Author keywords: Earthquake engineering; Engineering education; Hands-on experience; Hybrid simulation; Laboratory demonstration.

Background and Objectives

Bloom's taxonomy, which is a functional and essential classification of learning objectives within education, divides educational objectives into three domains, namely, (1) cognitive, (2) affective, and (3) psychomotor (Bloom et al. 1956). One of the goals of current teaching techniques is to motivate educators to focus on all three domains, creating a more holistic form of education.

On the teaching frontier of civil engineering, two objectives remain in the core of the teaching methods, namely, (1) effective demonstrations that apply the presented theories and methodologies, and (2) hands-on experience where students conduct simulations or experiments themselves. The first objective is related to cognitive and affective domains of Bloom's taxonomy, whereas the second objective is in tandem with the psychomotor domain. At the University of California, Berkeley (UCB), a structural engineering demonstration laboratory named after Professor T.Y. Lin is in operation, in which computer simulations and physical testing are intended to be conducted during lecturing time. Because this demonstration laboratory resides in one of the lecture rooms in the Civil and Environmental Engineering (CEE) building, space and safety considerations hinder large-scale structural demonstrations to students, restricting testing only to small-scale structural components (e.g., steel columns). In addition to the laboratories in the CEE building, experimental facilities at the UCB include the equipment site of the Network for Earthquake Engineering Simulation (NEES), which is also called nees@berkeley, and the shaking-table facility operated by the Pacific Earthquake Engineering Research (PEER) Center. These facilities are available for demonstrations and hands-on-experience tests. In particular, a small-scale setup, referred to as μ-nees setup, is used for development and demonstration purposes and is suitable for the considered objectives.

Hybrid simulation (HS) testing method combined with hands-on experience is one of the most suitable methods for demonstration and education in the areas of structural and earthquake engineering. The objective of this paper is to explore teaching innovations utilizing the versatility introduced by the HS testing method, specifically creating instructional case studies to aid in developing a modern course in earthquake engineering for high school and first-year undergraduate students.

Current State of Knowledge

HS

The HS method, also known as online or pseudodynamic testing, encompasses the realism of true dynamic testing using shaking tables and the simplicity of the more practical quasistatic experimentation. The potential of HS is enormous (Mosalam 1996), especially if coupled with substructuring techniques (Dermitzakis and Mahin 1985). In this method, critical components, e.g., those that are expected to undergo severe inelastic deformations during strong ground motion, are physically modeled (experimental substructure), while the rest of the structure is numerically idealized (analytical substructure) in the solution process of the structural response (Fig. 1). In many cases of full-scale studies, HS represents the only possible approach for investigating complex structural systems.

Previous studies have proposed HS using analog computer (Hakuno et al. 1969) and digital computer (Takanashi et al. 1975). A U.S.–Japan Cooperative Earthquake Research Program in the

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Note. This manuscript was submitted on May 16, 2012; approved on November 26, 2012; published online on November 28, 2012. Discussion period open until December 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Professional Issues in Engineering Education & Practice***, Vol. 139, No. 3, July 1, 2013. © ASCE, ISSN 1052-3928/2013/3-177-186/$25.00.

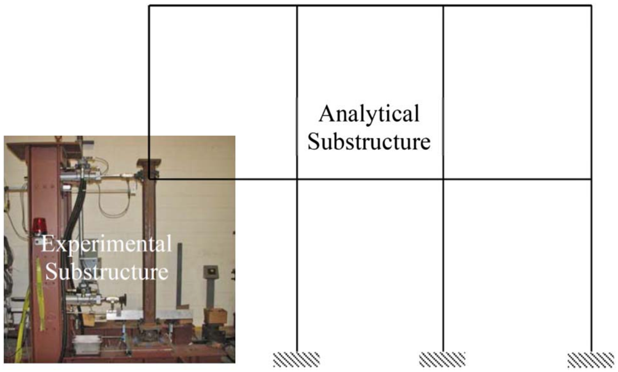

Fig. 1. A typical hybrid structure consisting of experimental and analytical substructures

1980s provided impetus for further development (Takanashi and Nakashima 1987), with significant research in the United States primarily at the UCB (Mahin et al. 1989) and University of Michigan, Ann Arbor, Michigan (McClamroch et al. 1981). This research focused on accuracy verification of the test method, and investigation into control of certain experimental intricacies affecting the test. The research efforts that took place after the development of the HS until current date can be categorized into five main research areas, namely, (1) development of substructuring techniques, (2) investigation of the effect of experimental errors, (3) development of suitable integration algorithms, (4) geographically distributed HS, and (5) real-time HS (RTHS). Regarding the first research area previously mentioned, the HS method is versatile and gaining popularity because of its ability to partition a structure into physically tested experimental substructures and mathematically modeled substructures.

Every innovation brings its own benefits and challenges. If the benefits gained by the realization of the innovation are worth the efforts spent to handle the challenges, resources are allocated for the relevant research to overcome these challenges. In the case of HS, the challenges are the requirements for accurate control and specialized integration algorithms that arise due to the presence of physically tested substructures. Hence, an experimentalist should pay more attention to the control settings in a HS test compared with a nonhybrid test. Similarly, an analyst should spend more effort on the selection of a proper integration method in a HS test compared with a pure numerical simulation. Presence of the first challenge necessitated investigation of the effect of experimental errors on the method and research has been conducted to reduce effects of errors on HS. The second challenge necessitated investigation of the suitability of existing integration methods, developed for pure numerical simulations, for HS and the development of specialized integration methods.

Conventional HS with slow rates of loading is sufficient for substructure testing in most cases where rate effects are not important. However, for rate-dependent materials and devices, e.g., viscous dampers or friction pendulum bearings, RTHS is essential. Dynamic actuators and a digital servomechanism have been used in the early stages of RTHS (Nakashima et al. 1992). Rapid development of computing technologies and control methods increased the RTHS research in recent years (Bonnet et al. 2008).

The unique feature of the HS method is to partition a structure into experimental and analytical substructures, allowing the use of more than a single experimental site, i.e., the ability to conduct geographically distributed testing where these different laboratories and computers are linked by high-speed communication networks. This concept was initially mentioned in a previous study (Campbell and Stojadinovic 1998). Distributed hybrid tests have been conducted first between Japan and Korea (Watanabe et al. 2001) and in Taiwan (Tsai et al. 2003). In the United States, a study coordinated by the Earthquake Engineering Research Institute (EERI) and supported by the National Science Foundation and the National Institute of Standards and Technology recommended upgrading the earthquake engineering experimental research infrastructure in the United States and development of NEES (Bordogna 1999). Accordingly, several modern testing facilities for experimentation and simulation are now available at different laboratories. Full use of these facilities resides in the idea of full system integration. A fundamental step toward this integration for research and education is the development of hybrid experimentation and simulation methodology using the online testing coupled with substructuring. The consequence of this approach involving geographically distributed HS is summarized as follows:

- Testing multiple physical components of a complex structural system at remote experimental facilities to understand the behavior of real structural systems;
- Optimizing use of testing and computational resources nationwide and worldwide to address grand challenges in earthquake engineering;
- Integration of physical modeling and computer simulations to study hybrid structural systems where benefits include utilizing computational advances and developing reliable models for the tested parts;
- Allowing real-time demonstrations during lecturing (demonstrations that can take place within the lecturing session or separately as another session following the lectures) to improve students' understanding of structural behavior of complex systems when subjected to different loading protocols. These demonstrations may include real-time simulations in the case of using dynamic actuators (Günay and Mosalam 2012).

As mentioned previously, this study focuses on the fourth item above.

Teaching Methods

The exposition below focuses on methods that can be used in illustrative teaching of the response of structures under earthquake excitations. These techniques involve problem-based learning, active and cooperative learning, interactive software, case studies, and rapid feedback.

A common complaint among employers and educators is that in many cases students are unable to effectively approach and solve new problems. This inability may be associated with students' weak grasp of fundamental concepts or their inability to apply known concepts to new problems. In recent years, much effort has been directed to finding methods that are more efficient to give students the problem-solving skills that they need (Wankat and Oreovicz 1993). These new methods rely on actively involving students in the learning process and providing them with rapid feedback (Johnson 1999; Mehta 1995). There are several methods promoting active learning in engineering (Richards et al. 1995; Roy 1998). One such method is interactive software, which can be used to study and visualize the effects of different parameters on the outcome of a complicated problem. A student may only be able to manually work through few complicated problems as a homework assignment, but with interactive visual software, the student can focus on interpreting the results and the effects of different variables. Moreover, the visual nature of the output allows students to grasp difficult concepts in a shorter time. A complement to the use of interactive software is programming

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assignments (Godfery 1998) in a higher level language such as *MATLAB* (MathWorks 2007). Students gain necessary skills to translate engineering problems into a programming language with the use of interactive software. This approach not only teaches programming but also exposes any deficiencies in the understanding.

Another active learning method is case studies (Deierlein et al. 1993; Gorman et al. 1995) as they push students into solving open-ended ill-structured real-world problems that may involve factors such as risk and uncertainty, trade-off and priorities, ethics, human elements, and impact assessment (Richards et al. 1995). Moreover, such problems may have multiple solutions with each solution having its own benefits. Case studies require considering multiple factors and integrate information from various sources. Because case studies involve learning skills at different levels of Bloom's taxonomy, they represent one of the most effective active learning methods.

Rapid feedback is another learning method that enhances the learning process in addition to the involvement of students more actively in this process. It allows instructors to determine how well students are learning and allows students to determine how well they understand the material. From this feedback, both instructors and students can take the necessary corrective actions. Traditional tools for rapidly measuring student performance are questions during lecture, short quizzes, clickers, or flashcards. Although such tools are useful indicators of how well students understand the lectures, they do not allow students and instructors to obtain feedback outside classes. For rapid feedback outside the classroom and to enhance the active learning process, the Internet is increasingly becoming the tool of choice (Frymier 1998; Wallace and Mutooni 1997). In the teaching experience described in the following section, feedback from students' surveys was used successfully to modify one of the hands-on-experience experiments.

The availability of class materials and online resources allows students to access the information when they are ready to study. The ability to run simulations, observe experiments, and take interactive homework assignments and quizzes allows students to evaluate their own understanding when the material is fresh in their minds. This is important because the self-evaluation of the students' understanding can help building their self-esteem and confidence, which are crucial for their future success. In conjunction with the World Wide Web, the use of multimedia support in engineering education can be an effective teaching tool (Deierlein et al. 1993; Hotchkiss 1994). For example, a video tape in a research area (e.g., earthquake engineering with case studies) can be valuable in outreach programs. All of these tools and techniques can be quite useful in teaching and advancing the state of knowledge in earthquake engineering.

Case Study Involving HS as a Teaching Experience

Brief Description of Program

An example of both theoretical and hands-on-experience program in structural engineering was developed at the UCB for high-school students participating in the National Student Leadership Conference (NSLC). The objective of the activity was to develop and test an educational outreach program that would increase the interest of U.S. high school students in undergraduate engineering programs. The results and student feedback from such outreach programs are crucial for enhancing existing programs, such as the K-12 engineering outreach program of nees@berkeley, and also for developing similar programs, such as the instructional case studies involving the test setups explained later, in the future. The program was also aimed to meet the NSLC goal of providing the next generation leaders with information and inspiration in developing their potential and selecting a successful career. The educational program was conducted in three sessions, in which 108 students participated. Each session included lectures, laboratory demonstrations, and hands-on experience that took place at nees@berkeley. The activities were conducted by one professor, three graduate students, and laboratory staff.

Background of Students

The students came from the engineering program offered by the NSLC to the high school students during the summer vacation. The admission to any NSLC program is very competitive and it has hosted tens of thousands of outstanding high school students from across the United States and more than 45 other countries since 1989. There are several ways in which students are selected to participate in the NSLC. Teachers, counselors, and NSLC alumni can nominate outstanding high school students to participate in the NSLC. Candidates may also be selected from one of several national talent identification surveys. Interested students who possess strong academic records and have demonstrated leadership potential may apply directly.

Students who participated in this NSLC program had strong interest and knowledge in technical sciences. The majority of them (more than 70% on average) were planning to select one of the engineering fields as a career (Table 1). Some students had vague understanding of particular engineering fields. Therefore, one of the goals of the NSLC program was to provide a detailed introduction of earthquake engineering field with hands-on experience to help the students to acquire clearly defined and accurate future expectations. It should be noted that although the NSLC program has been in place since 1989, HS was introduced into this program for the first time during the summer of 2006 at the UCB. A total of 108 students participated at the UCB program in three sessions, 39 students in Session 1, 28 in Session 2, and 41 in Session 3.

Students' Activities

Each session was conducted at nees@berkeley in Richmond Field Station. The students had three types of activities, namely, lectures, demonstrations, and hands-on experience.

Lectures

The lectures, delivered by the first author, were about earthquake engineering and its application to seismic stability of wood-frame buildings. The lectures were aimed for a high school-student level and were delivered on 2 separate days. The objective of the lectures was to introduce earthquake engineering to the students and to connect this topic with the behavior of wood-frame houses. As a direct continuation of the lectures, the students were asked to perform hands-on activities at the nees@berkeley testing facility.

The first lecture was an overview of earthquake engineering. The lecture started with the explanation of the causes of earthquakes and typical sources of ground shaking, and ended with the seismic effects on structures. The topics covered in the first

Table 1. Interests of Participating Students in Career Fields

Field	Session 1	Session 2	Session 3	Average
Engineering (%)	69.2	82.1	63.4	71.6
Other (%)	12.8	10.7	14.6	12.7
Undecided (%)	18.0	7.2	22.0	15.7

Note: These data were obtained before the program.

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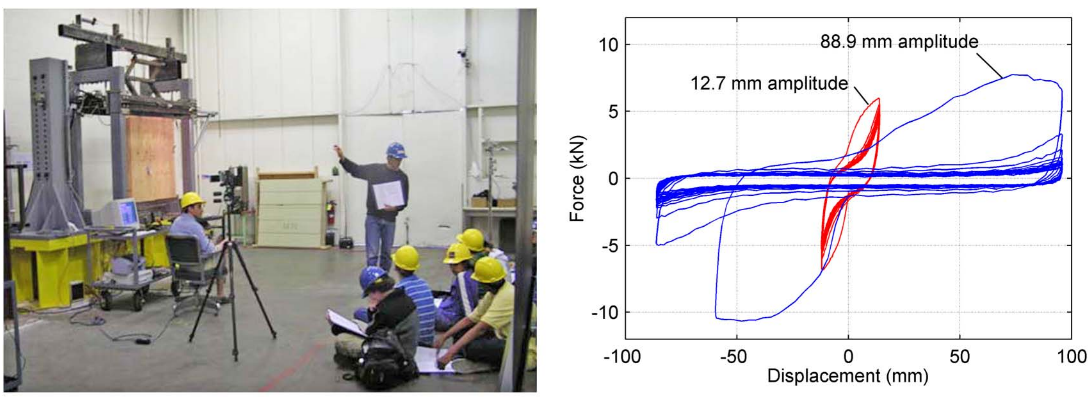
lecture also included convective currents theories, types of interplate boundaries, types of faults, elastic rebound theory, seismic waves, seismographs, concepts of magnitude and intensity, inertia forces, and flow of inertia forces through the structural components. The second lecture was oriented to architectural and structural features of wood-frame buildings affecting their response to earthquakes. The topics covered in this lecture included twisting of buildings, seismic design philosophy, ductility, flexibility, effect of soil conditions, load path of inertia forces in a wood house, architectural irregularities, wall action for resisting lateral force, and typical wood-wall components. The second lecture ended with a video showing a shaking-table test of a full-scale 2-story wood house. This video was part of a full-scale testing of a wood-frame building under earthquake loading by means of a seismic simulator, i.e., shaking table.

Demonstration and Laboratory Tours

The program activities of each session included two live test demonstrations and a tour of the experimental facilities of the PEER Center and nees@berkeley (both located at Richmond Field Station). On day 1, the students participated in the demonstration of cyclic loading of a 1.22×1.22 m$(4 \times 4$ ft$)$ wood panel specimen. The objective of this demonstration was to introduce the cyclic performance of a typical wood panel to the students, similar to the one that they would build. From the test, they could identify how a wood panel performed and failed during an earthquake. The panel was constructed with studs at 305 mm (12 in.) spacing and sheathed with a plywood sheet on one side nailed to the frame using 305 mm (12 in.) nail spacing. Fig. 2(a) shows the test setup with the specimen installed. In the first test, the panel was subjected to 12.7 mm (0.5 in.) amplitude cycles. At this amplitude, the panel did not reach its shear load-carrying capacity and strength degradation was not observed. The second test was performed with 88.9 mm (3.5 in.) amplitude cycles, in which the panel reached the shear load-carrying capacity during the first cycle and its strength was dramatically reduced for the subsequent cycles. Fig. 2(b) shows the force versus deformation curve of one of the demonstration tests.

On day 2, the students had a laboratory tour of the experimental facilities at the PEER Center and nees@berkeley. First, a 20-min tour of the shaking table was conducted with the guidance of a staff engineer. During the tour, the main performance characteristics of the shaking table, some details of the hydraulic power supply and data acquisition were discussed. Second, several experimental setups utilizing high-performance actuators and reconfigurable reaction wall, test fixtures, and test specimens, currently installed in the PEER and nees@berkeley laboratories, were demonstrated and discussed. Introduction and basic information on geographically distributed HS based on usage of the facility were briefly discussed.

On day 3, the students witnessed a HS demonstration of a full-scale wood-frame test subjected to earthquake loading in the nees@berkeley laboratory. With this HS test, the students were able to identify the behavior of the wood frame and they could infer the seismic behavior of a whole house. The HS test was conducted using two parallel wood walls measuring 5.94×2.59 m $(19.5 \times 8.5$ ft$)$. The walls were sheared at the top using a steel



(a) (b)

Fig. 2. Cyclic test demonstration of a 1.22×1.22 $m(4 \times 4$ ft$)$ wood panel: (a) test setup; (b) force–displacement relationship

(a) (b)

Fig. 3. Full-scale HS test of first-story longitudinal walls of a three-dimensional shaking-table test: (a) HS experiment; (b) shaking-table experiment

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loading frame attached to an actuator as shown in Fig. 3(a). The actuator was driven by the commands computed using numerical integration, where the equations of motion were solved using the force data measured at each time step. The measured force data represented the nonlinear response characteristics of the tested walls, which represent the first story walls of a three-dimensional structure tested on the shaking table [Fig. 3(b)]. By contrast, the dynamic characteristics (inertia and damping) and the second story of the structure tested on the shaking table were computationally modeled. The gravity load was applied using three vertical links connecting the steel loading frame to the floor. The test was performed using two consecutive Loma Prieta earthquake records scaled to 0.66g peak ground acceleration.

For the wood-frame test demonstration, students were divided in two groups. The first group was inside the control room with a graduate student and a staff engineer, observing the control computers and the resulting graphs. The second group was next to the specimen with another graduate student explaining the test setup, test specimen design, and the instrumentation. The two groups of students were switched at the middle of the test. Fig. 4 shows comparisons between the results of the HS and past shaking-table tests.

Hands-on Experiences

The students performed three hands-on-experience activities—compression test, panel construction, and panel shear test. For the activities, the students were divided into two groups, namely, A and B.

At the axial compression test station, the students learned and compared engineering properties of common construction materials such as wood and concrete. At this station, the students performed compression tests on a concrete cylinder and wood blocks parallel and perpendicular to the grains. Fig. 5(a) shows a group of students in the axial compression test station, where the compression test machine and the data-acquisition (DAQ) system were controlled by a graduate student and a staff engineer. For each axial test, the students recorded the force and displacement measurements and computed the corresponding stresses and strains. They plotted the stress-strain curves of the three tests and computed the modulus of elasticity of the materials. Typical results from the axial compression tests are shown in Fig. 5(b). This exercise helped the students to identify and compare material strength, stiffness, and failure strain. Furthermore, students identified the failure mode of each specimen from failure patterns provided in their handouts.

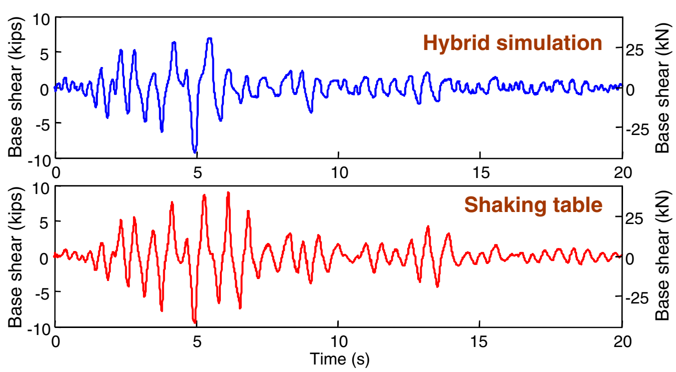
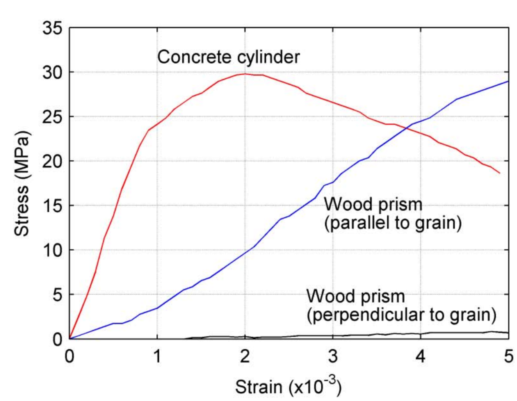


Fig. 4. Comparison of HS and shaking-table test results

At the panel-construction station, the students constructed 1.22×1.22 m(4×4 ft) wood panels from studs, nails, and plywood sheets or shiplap boards. For this activity, the students were divided into groups of four or five. For each session, the students built panels with three configurations using different nailing schedules, stud spacing, and wood panel sheathing, resulting in a total of 24 panels consisting of nine configurations. The frame consisted of top and bottom plates and vertical studs, where the studs and plates were 38.1×88.9 mm (nominally, 2×4 in.) Douglas Fir structural wood. The majority of frames had four vertical studs spaced at 406 mm (16 in.). The studs were connected to the top and bottom plates by means of 16d nails, while the sheathing (plywood or shiplap) was nailed to the frame members with 8d nails. The panel-construction activity started with a brief introduction of safety procedures by two graduate students. They also explained how to hammer and safely pull out the nails. For panel construction, each student had a step-by-step manual with illustrative drawings. During the construction, the students were also guided by the two graduate students. The steps of the construction are as follows:

- Measure the sample panel specimen and record all member dimensions and nails spacing;
- Mark with pencil the place where the vertical studs meet the top and bottom plates;
- Place vertical studs on the bottom plate and hammer with 16d nails;
- Place the top plate on the studs and nail with 16d nails;
- Place the panel flat on the ground and place the plywood or shiplap on top of the panel;
- Measure where nails should be and nail plywood or shiplap to the panel with 8d nails; and
- Repeat the nailing for the other panel face (when double-sided design was required).

(a)



(b)

Fig. 5. Axial load station for Session 2: (a) test setup; (b) stress-strain relationships

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After completing the construction, each group had to list possible failure modes that could occur to their panel based on the cyclic tests that they had observed in the demonstration a day earlier. At the panel test station, the students performed a monotonic shear test on their wood panels. This activity was guided by two graduate students, who controlled the test machine and helped the high school students to bolt their specimen into the test setup as shown in Fig. 6. Before the test, the students were instructed with basic concepts of experimental research. They learned about actuators, hydraulic pumps, hydraulic power supply, system control theory, and instruments monitoring the panels during the test.

Each specimen, previously constructed by a particular group of students, was installed in the set up by the same group. The panel was subjected to a monotonic test by shearing the panel up to 130 mm (5 in.) horizontal displacement. For each test, the students watched the failure mode and identified the weak links in the wall in response to the shear loading. The force–displacement curve was generated for each wall and displayed on a large screen. From these curves, the students determined the strength of the panels and compared the results of panels with different configurations. By analyzing the curves and correlating with the observed damage, the students concluded how different configurations affect the panel behavior. Examples are shown in Fig. 7 for force–deformation curves of panels tested during Sessions 2 and 3.

Fig. 6. Installation of panel constructed by a student group in the test setup

Feedback from the Case Study

Two types of feedback were obtained from the outreach program at the UCB, namely, (1) objective feedback based on anonymous evaluation forms completed by the high school students and (2) subjective feedback based on commentaries of students and their oral appreciation of the work performed by the graduate students, the professor, and staff who participated in the program. To estimate the effectiveness of the program, the students were asked to complete anonymous evaluation forms before and after the program. A summary of rating of each part of the program is presented in Table 2 (scale of 0–100%, with 100% being the best). The resulting rating is considered as satisfactory considering the fact that the high school students were in a summer program and they were expecting to have less physical and academic work.

The demonstrations and laboratory tour had high ranking scores (average 73% in Table 2), mainly because of the HS full-scale demonstration on day 3. Witnessing this HS demonstration, the students were able to observe the seismic behavior of a pair of wood panels and were able to infer the seismic performance of a complete house. In fact, the students were able to achieve comprehensive understanding of the response of structures by fulfilling the cognitive and affective learning objectives of Bloom's taxonomy. This HS demonstration was a unique case study for the students. Combined with the lectures and hands-on experience, this case study exposed the students to a deeper learning experience of earthquake

Table 2. Average Ratings of Program and Activities

	Session			
Rated activity	1	2	3	Average
Lectures (%)	70.0	70.0	54.0	64.7
Demonstrations and laboratory tours (%)	76.0	74.0	69.0	73.0
Axial compression test station (%)	52.0	56.0	61.0	56.3
Panel-construction station (%)	84.0	84.0	80.0	82.7
Panel test station (%)	68.0	78.0	67.0	71.0
Overall (%)	68.0	72.0	67.0	69.0

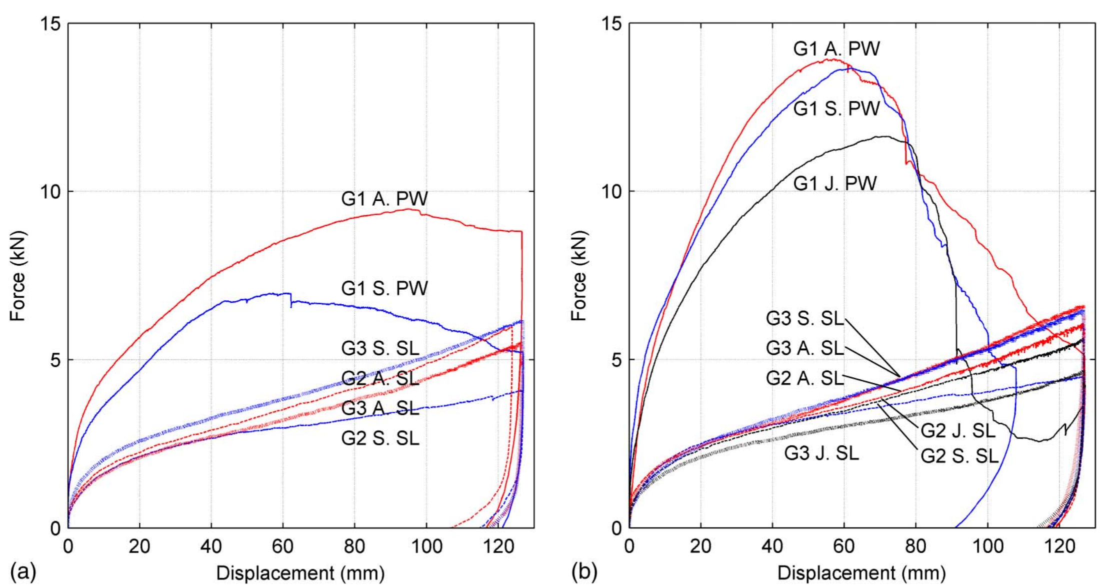

Fig. 7. Force–deformation results of panel tests: (a) Session 2; (b) Session 3

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engineering. The positive feedback obtained from the students about the HS demonstration confirmed the benefits of HS in teaching earthquake engineering concepts and represented the motivation for the development of set ups suitable for broader HS demonstrations as will be explained in the following section.

There were two other reasons for the high scores of the demonstrations and laboratory tours. First, witnessing equipment capable of moving full-size structures at earthquake-loading rates had an impressive effect on the students. Second, the demonstrations showed the use of testing equipment not only on reduced-scale but also on full-scale specimens.

The high rating of the lectures can be explained by their short duration (compact presentation with many test movie clips to keep students interested), the proper orientation, and the strong link between elements of the program. The duration of lectures was intentionally made short without going into details, such that students were not overwhelmed with many technical details and they had more time for demonstrations and hands-on experience. An important feature of the lectures was their proper level targeting high school students, in which they were taught at a simplified level, so that all the students could understand the basic concepts. Finally, the lectures were used to connect all the hands-on activities with the principles of earthquake engineering and applications to seismic stability of wood-frame houses. The connection between the lectures and the hands-on experience was made by the explanation of the purpose of each demonstration and hands-on activity. The difficulty level of material taught during the program is reflected in the percentages of student answers, as presented in Table 3.

Hands-on experience is an efficient and widely used teaching technique in engineering education. Because of the complexity of civil systems, these experiences are sometimes difficult to implement in such a way that the students can learn difficult engineering concepts from them. As an example, in the panel-construction station, the students had some predefined panels to build. Three types of panel designs were selected to be built during each session, where different panels in each session had only one variable in the configuration (e.g., nail spacing). Based on the examination of the panel test results, the students realized how different configurations can affect the panel behavior. Moreover, by observing the behavior of each type of panel, the students arrived at important conclusions about factors affecting the panel structural behavior. If the students were let alone to build any type of panel, they may have constructed totally different ones and this would not have allowed identifying how much the strength changes with a single variation of the structural configuration. The rating of the hands-on experience (Table 2) indicated that the panel-construction station received the best rating of all activities. The average rating of this activity was above 80%. This high rating can be explained by several reasons. First, the construction of the panels was performed in teams where students interacted with each other. Second, some elements of competition with a goal of making better and stronger panel made this activity more attractive to the students. Third, the construction of the panels with good quality resulted in the satisfaction of an accomplished goal by the students. Fourth, the students were enjoying nice summer weather outdoors.

The ratings of the axial compression test station were somewhat low. There are several reasons to explain this low rating. First, the test setup used an old compression test machine with a simple not interesting test setup compared with the new equipment used in other parts of the laboratory. Second, the compression test was conducted at a slow less exciting speed. Third, test specimens were too simple to motivate the students and tests had predictive outcomes. Using student feedback, the last shortcoming was corrected by introducing new test specimens toward the end of the program in the second half of Session 2 and Session 3. According to this modification, a hollow cylindrical thin-wall can and a short piece of a tube with a square cross section were compressed. The students enjoyed witnessing the buckling of the specimens in a multistage process with an incredibly regular buckled shape as shown in Fig. 8. This program modification caused a steady increase of the student interest in this station from session to session (Table 2).

The panel test station was a direct continuation of the panel-construction station. Therefore, the ratings of both activities were strongly correlated. However, the rating of the panel test station was somewhat lower than that of the panel-construction station. This can be explained by a relatively long downtime between the tests because installation of the test specimen required some time and only the group associated with the specimen was involved in the process, whereas the other groups were waiting during this downtime.

The overall reaction of the students was very positive as shown in Table 4, with more than 80% of the students on average willing to recommend the UCB program to others. The fact that the students positively rated the program was also reflected in the comments and testimonials of the evaluation forms. An appreciation

Table 3. Students' Evaluation of the Difficulty Level of Presented Material for All Activities Combined

Answer	Session 1	Session 2	Session 3	Average
Hard or slightly hard (%)	17.8	21.4	4.9	14.7
Average or just fine (%)	69.3	53.6	75.6	66.2
Easy (%)	10.3	14.3	19.5	14.7
Not interesting (%)	2.6	3.6	0.0	2.1
No answer (%)	0.0	7.1	0.0	2.4

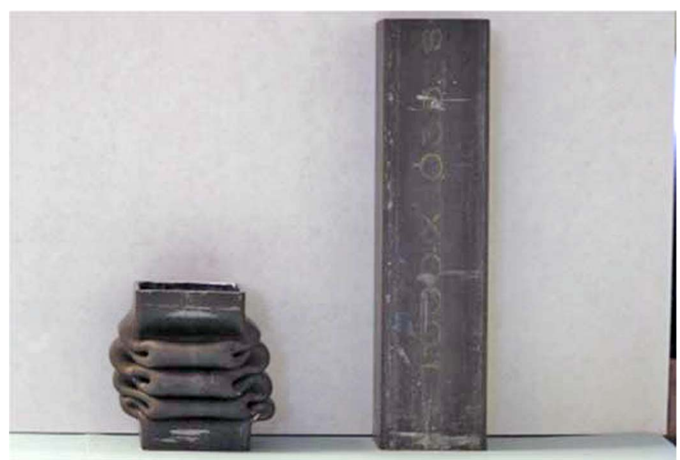

Fig. 8. Thin-wall tube section before and after compression test (only for Sessions 2 and 3)

Table 4. Would a Student Recommend the nees@berkeley Program to Others?

Answer	Session 1	Session 2	Session 3	Average
Yes (%)	79.5	89.3	75.6	81.5
No (%)	20.5	10.7	9.8	13.7
No answer (%)	0.0	0.0	17.1	5.7

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of efforts by the nees@berkeley and the PEER team who prepared and conducted the program was expressed in many comments. A conclusion can be drawn from a student comment of Session 1: "Thank you very much for this experience. It gave me an idea of what civil engineering is like."

Experimental Setups for Instructional Programs and Courses

In order to be able to achieve the students' comprehensive understanding of the response of structures to earthquake ground motions by demonstrations, that is, to fulfill the cognitive and affective learning objectives of Bloom's taxonomy, the demonstrations should cover a broad range of parameters and several values of each parameter. This target involves the construction of many different structural configurations, which is not possible to be completed during the practical duration of a series of demonstrations. However, HS, where it is quick and easy to change the structural configuration on the computer and demonstrate the effect of these variations on the tested substructure, is suitable for demonstrations.

The experiences gathered from the HS demonstration presented in the previous section and developed at the UCB laboratories are used to create new instructional case studies to aid in the development of a modern course in earthquake engineering. Two experimental setups and their planned usage in the instructional case studies are described in this section. These test setups are planned to replace the previously discussed costly and time-consuming full-scale wood-frame demonstration tests conducted in the nees@berkeley laboratory.

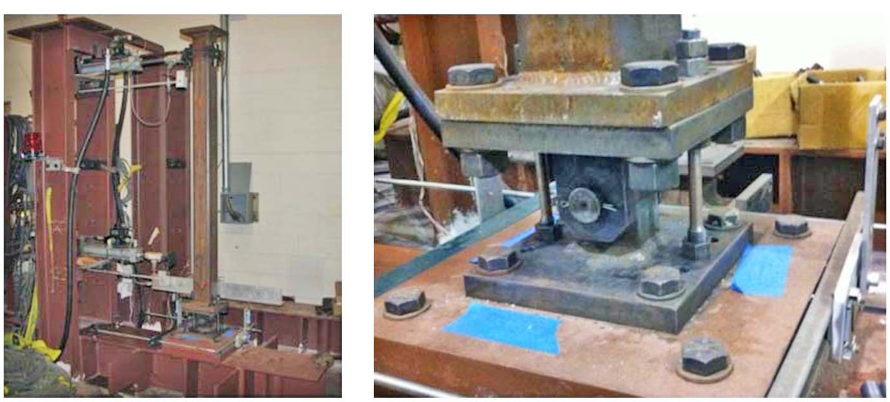
Experimental Setup I: μ-nees

The μ-nees setup (Fig. 9) consists of a self-equilibrating reaction frame designed to support an actuator and a test specimen loaded statically or dynamically. Observable from Fig. 9, the specimen consists of a steel column mounted on top of a special clevis with replaceable steel coupons. The column size is chosen such that no yielding takes place at the column and the nonlinear hysteretic behavior takes place at the replaceable coupons. By using different coupon design configurations, it is possible to obtain various levels and types of hysteretic behaviors. Although one of the actuators seems to be idle in Fig. 9, this set up can accommodate two independent or coupled experimental degrees of freedom by different configuration of the shown 53.37-kN dynamic actuators [stroke $= \pm 254$ mm(± 10 in.)]. The attached servo valve results in a velocity limit of 584 mm/s(23 in./s), allowing the use of the set up for real-time testing. This set up was previously used for various aspects of HS development including RTHS, geographically distributed testing, mixed displacement and force controls, control switching, and recently for RTHS involving large computational models.

A hybrid model that can be developed using this set up is shown in Fig. 1. The parameters that could be studied using the μ-nees setup are the number of stories, number of bays, stiffness, strength and mass distribution along the elevation and plan of the structure, and the type of ground motion. These parameters, within the context of the HS methodology, can be easily changed during an educational program because they only require changing the input data of the computational model, rather than changes in the physical test specimen. Depending on the emphasis of the educational program, the instructor may prioritize the parameters to be changed if time limitations require conducting limited numbers of HS runs.

The dynamic characteristics of a structure depend on the interaction of the stiffness of the structure with its mass, which is mainly contributed by, e.g., the mass of the floors, structural walls, infill walls, beams, columns, and the mass of the live contents such as furniture and people. The response of a structure during an earthquake is a function of its dynamic properties. Therefore, it is beneficial to demonstrate the effect of the stiffness and mass on the dynamic characteristics and the response of a structure for a fundamental understanding and appreciation of this interaction by the students. The numbers of bays and stories also affect the stiffness and mass and accordingly the dynamic characteristics. One can use the number of bays and stories as descriptors for the structure to facilitate an easier classification for students. For example, the structures with large number of stories represent tall structures in big city centers and structures with large number of bays represent shopping malls. It is also possible to demonstrate the response differences of structures constructed with different structural materials such as reinforced concrete, steel, or wood structures. For a certain structural configuration, the responses of these structures, designed to satisfy code requirements, are different. Accordingly, it is important to demonstrate to the students, the response differences introduced by different construction materials. Although the test substructure in Fig. 9 is a steel structure, it is possible to achieve the mass and structural properties of the analytical substructure corresponding to any type of material. Besides, with the proposed set up it is possible to approximately resemble characteristics of other materials by changing the coupon design and its material.

The distribution of mass and stiffness along the elevation and plan of a structure is critical for its seismic behavior. With the proposed set up, the effect of nonuniform stiffness and mass can



(a) (b)

Fig. 9. μ-nees laboratory used in instructional case studies: (a) test setup; (b) bottom coupon details

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be incorporated in the analytical model of the HS and the resulting effect can be demonstrated to the students. The stiffness and strength of a certain story being less than 75% of those of the adjacent stories will result in soft and weak stories, respectively. After the students observe the response degradation introduced by the presence of a soft story, they can appreciate the meaning of a building tagged as a soft story, e.g., in the San Francisco Bay Area, to increase the earthquake awareness and to encourage initiating retrofit measures.

The effect of the ground-motion characteristics on the seismic behavior of structures can also be displayed through the HS demonstrations. Ground motions initiated by an earthquake are classified as near-fault and ordinary ground motions. As the name implies, near-fault ground motions occur close to the fault within distances less than 20 km. Structures respond differently under the effect of near-fault and ordinary ground motions. Near-fault ground motions, characterized by the presence of a few dominant velocity pulses, impose large demands on structures compared with ordinary ground motions (Alavi and Krawinkler 2004). The students can have better understanding of this response difference after observing it in a HS demonstration. In addition to the dynamic characteristics of a structure, frequency content of a ground motion affects the response of a structure. A ground motion that contains a dominant frequency that is close to a natural frequency of the structure imposes a large demand on the structure. This increase in demand is related to the resonance phenomenon, which is taught in high school physics classes. Because of the versatility of the HS method, it is possible to experimentally demonstrate this effect on tall buildings, without the need to construct a complex tall building. An example of tall buildings affected by ground motions containing dominant low frequencies is the 1985 Mexico City earthquake, where high-rise buildings were extensively damaged.

Experimental Setup II: Small Shaking Table

The second setup, located at the UCB structural testing laboratory, consists of a small [1.22×1.22 m(4×4 ft)] high-fidelity shaking table that can reproduce target accelerations accurately up to 20-Hz frequency. The shaking table is composed of a steel platform moving on supporting rollers. The platform is attached to a 111.20 kN, ± 127 mm(± 5 in.) dynamic actuator that can accommodate velocities up to 889 mm/s.(35 in./s.). Two steel beams placed close to the ends of the platform are used as hold-down systems to prevent the uplift due to overturning moments caused by the inertia force of a test specimen. This set up was used for conventional shaking-table testing and RTHS (Günay et al. 2012). Components of the RTHS framework are shown in Fig. 10.

This set up can be used effectively for demonstrating the effect of excitation characteristics on the response of structures, including demonstrations of the effects of ground-motion type and frequency content. Application of harmonic excitations with different frequency content is particularly useful for direct observation of resonance. Explaining that each ground motion can be represented by the sum of an infinite number of harmonic excitations, where only some of the harmonic excitations are dominant, and displaying the resonance effect lead to clear visualization of the concept by the students.

Similar to the μ-nees setup, response difference of structures with different number of stories can be demonstrated with the shaking table. It is possible to test the top one or two stories of low-, medium-, and high-rise structures, where the rest of the structure is modeled as an analytical substructure. This set up is also useful to demonstrate advanced concepts, e.g., innovative technologies such as base isolation.

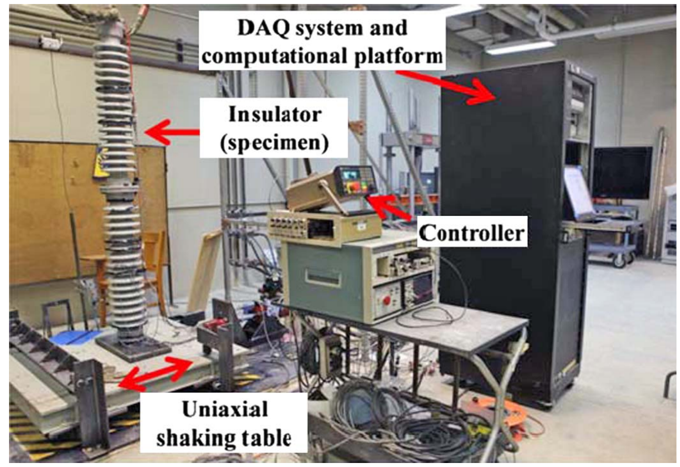

Fig. 10. Components of RTHS in test setup II for an insulator post of a disconnect switch

Depending on the characteristics of the structure and the soil that it is built on, the soil characteristics can alter the response of the structure. In such cases, ground motions recorded by accelerometers in the free field become inadequate to determine the structural response. This situation particularly occurs when the structure is stiff compared with the underlying soil. The small shaking-table setup is useful for the demonstration of this effect where it is possible to model the underlying soil as an analytical substructure. This demonstration is useful to broaden the students' understanding of the seismic response of structures.

In addition to the previously mentioned demonstrations, it is possible to use both set ups for hands-on-experience purposes. An example of such an application is the EERI seismic design competition for undergraduate students. In this competition, each participating student group designs and constructs a small-scale cost-effective multistory commercial office building for a combination of specified gravity and seismic loads, using a specified amount of wood material. The constructed structures are tested using a specified ground motion. Evaluation of performance is conducted not only for structural response but also by considering a cost–benefit analysis, where the structural response measured from testing of the structure is converted to a seismic monetary loss and added to the initial cost to compute the total loss. Subsequently, the total loss is subtracted from the revenue, which is computed as a function of the floor area to be rented or sold, to calculate the income. Employing a similar evaluation in a new course can be very effective to introduce the concept of performance-based earthquake engineering (PBEE), which combines various analysis stages, starting from definition of seismic hazard and ending with determination of monetary loss, in a probabilistic manner (Porter 2003). PBEE is gaining widespread use within the structural engineering profession. Therefore, introduction of this concept complementary to the students' design and construction experiences is of particular importance.

Concluding Remarks

A case study for teaching earthquake engineering that involved lectures, hands-on experiences, and HS demonstrations is presented. This case study involved different activities and integrated information from various sources at different levels of Bloom's taxonomy to maximize students learning in the cognitive, affective, and psychomotor domains. The hands-on experience involved

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design and construction of small-scale specimens and was used to obtain rapid feedback during the learning process. This feedback allowed to assess how well students understood and made use of the lectures and demonstrations.

It is concluded that HS-driven demonstration is an effective method for teaching earthquake engineering. The use of HS allows comprehensive learning of earthquake engineering concepts, e.g., effect of different materials, nonuniform stiffness and mass within a structure, number of bays and stories, ground-motion characteristics, frequency contents, and soil characteristics among others. The effectiveness of HS was confirmed by the students' positive feedback from the case study described in this paper.

Finally, two experimental setups with the capabilities to use HS (the μ-nees and the small high-fidelity shaking table) are described. These set ups are flexible and effective tools for teaching and demonstrating fundamental earthquake and structural engineering concepts to students.

Acknowledgments

The authors acknowledge the financial and organizational support of the NSLC. The educational outreach program discussed herein was conducted at the nees@berkeley experimental site, which is funded by the National Science Foundation though the George E. Brown, Jr. NEES. The assistance of several undergraduate and graduate students, especially Dr. Tarek Elkhoraibi, and staff of nees@berkeley is gratefully acknowledged.

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