Title

Promoting undergraduate interest in earthquake engineering and seismic design through a shake table competition.

Authors

Brandenberg, SJ
Gebman, M
Cheng, L
et al.

Publication Date

2023-12-11

Peer reviewed

PROMOTING UNDERGRADUATE INTEREST IN EARTHQUAKE ENGINEERING AND SEISMIC DESIGN THROUGH A SHAKE TABLE COMPETITION

M. Gebman[1], S. J. Brandenberg[2], L. Cheng[3], D. Chang[4], W. Lee[5], M. Pi[6], J. Ugalde[7], S. Ashford[8]

ABSTRACT

An undergraduate seismic design competition was developed by members of the Pacific Earthquake Engineering Research (PEER) Center Student Leadership Council (SLC). This competition was designed to physically demonstrate aspects of PEER's performance-based earthquake engineering methodology, and to educate and stimulate engineering undergraduate students via a hands-on project in a team environment. Teams design a balsa wood model of a multi-level commercial office structure that is subjected to a sequence of scaled ground motions from El Centro, Northridge and Kobe earthquakes, and the motion sequence corresponds to increasing spectral accelerations in the range of natural periods anticipated for the structures. Models are tested on a University Consortium on Instructional Shake Tables (UCIST) shaking table with simulated weights attached to each level. Accelerations are measured at the roof and base of the structure, and are subsequently processed to obtain measurements of engineering demand parameters (EDP's) that are correlated deterministically with dollar loss. Seismic performance is scored based on annual building revenue, which accounts for rent income, construction cost, and annual seismic cost. Three competitions have been held to date, two of which were sponsored by PEER, and the third sponsored by the Multi-Disciplinary Center for Earthquake Engineering Research (MCEER).

---

[1] Ph.D. Candidate, Dept. of Structural Engineering, University of California San Diego, La Jolla, CA 92093
[2] Assistant Professor, Dept. of Civil & Environmental Engineering, University of California Los Angeles, Los Angeles, CA 90095
[3] Assistant Professor, Dept. of Civil & Environmental Engineering, University of California Davis, Davis, CA 95616
[4] Ph.D. Candidate, Dept. of Civil & Environmental Engineering, University of California Davis, Davis, CA 95616
[5] Ph.D. Candidate, Dept. of Civil & Environmental Engineering, Stanford University, Stanford, CA 94305
[6] Graduate Research Assistant, Dept. of Civil & Environmental Engineering, University of California Davis, Davis, CA 95616
[7] Graduate Research Assistant, Dept. of Civil & Environmental Engineering, University of California Davis, Davis, CA 95616
[8] Associate Professor of Geotechnical Engineering, Dept. of Structural Engineering, University of California San Diego, La Jolla, CA 92093

Introduction

Members of the Student Leadership Council (SLC) for the Pacific Earthquake Engineering Research (PEER) Center developed an undergraduate seismic design competition in 2004, and the competition is now in its third year. The competition, though still in its infancy, has already expanded nationally by involving teams from all three national earthquake research centers across the United States. The competition provides students with the opportunity to apply classroom knowledge in a team environment, similar to other well known competitions such as the American Society of Civil Engineers (ASCE) National Concrete Canoe Competition, and the American Institute of Steel Construction (AISC) National Steel Bridge Competition. Thousands of students have participated in concrete canoe and steel bridge, and hopefully thousands will eventually participate in the seismic competition as it continues to grow and expand.

The objectives of the annual undergraduate seismic design competition are:

- To physically demonstrate aspects of performance-based earthquake engineering in the context of the PEER methodology, and to build awareness of the methodology among engineering students and practitioners, and the public.

- To educate undergraduate students about earthquake engineering and stimulate them to contribute to the profession.

- To demonstrate the value of PEER's Student Leadership Council (SLC) representatives and officers, who are a key liaison between PEER students and the PEER center.

This paper presents an overview of the technical and educational components of the seismic design competition. Detailed rules for the competition can be found on the SLC website (http://peer.berkeley.edu/students/Seismic.html), and only an abbreviated summary is presented herein. The performance-based earthquake engineering scoring system is presented, with focus on the implementation of aspects of the PEER methodology. The experimental setup, data acquisition features, and data processing methods are presented second. Finally, the educational value of the seismic competition is discussed, including results from past competitions and goals for future competitions.

Structural Design Task

Teams must design a multi-level commercial office building to resist severe earthquake loading, from scaled versions of ground motions recorded during the 1940 El Centro, 1994 Northridge and 1995 Kobe earthquakes. Teams need to also account for architectural and economic concerns (such as the maximization of premium office space) in their design. Teams are allowed to use lateral force resisting systems, which include: shear walls, moment connections, x-bracing, eccentric bracing, and dampers. To verify the seismic load resistance system teams must construct a scaled model from balsa wood, at a scale of 72:1, for testing on the UCIST shake table.

Performance-Based Earthquake Engineering Scoring System

The seismic competition physically demonstrates aspects of the performance-based earthquake engineering (PBEE) methodology as developed by the Pacific Earthquake Engineering Research (PEER) Center (e.g., Porter 2003). The PEER methodology involves four steps: 1. hazard analysis, 2. structural analysis, 3. damage analysis, and 4. loss analysis. Uncertainty in each step is integrated in the methodology, producing in the end estimates of the rate at which certain decision variables (e.g., dollar cost, loss of life) are exceeded. The seismic competition treats each of the components deterministically, and focuses primarily on the structural analysis component of the methodology. Treatment of each component is discussed in the sections that follow.

Hazard analysis

The seismic hazard for the site is represented by a set of three ground motions (Figure 1). Scaled versions of motions recorded during the 1940 El Centro, 1994 Northridge, and 1995 Kobe earthquakes are applied in that sequence to the base of each of the model structures. The motion sequence corresponds to increasing spectral accelerations in the anticipated structural natural period range of 0.2 s to 1.0 s. Return periods assigned to the motions are 50, 150 and 200 years for the El Centro, Northridge and Kobe motions, respectively. Calculation of annual seismic cost depends on motion return period, as explained later.

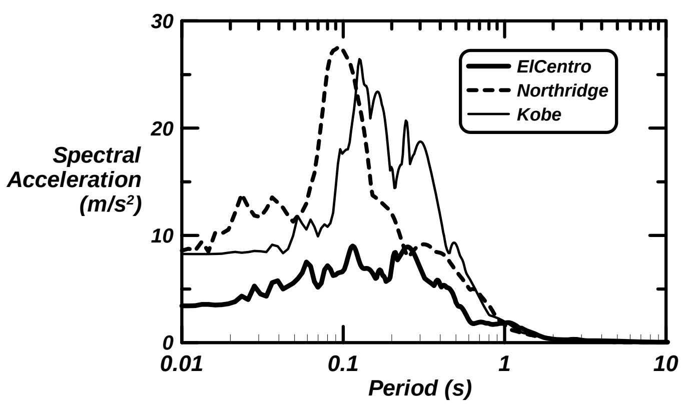
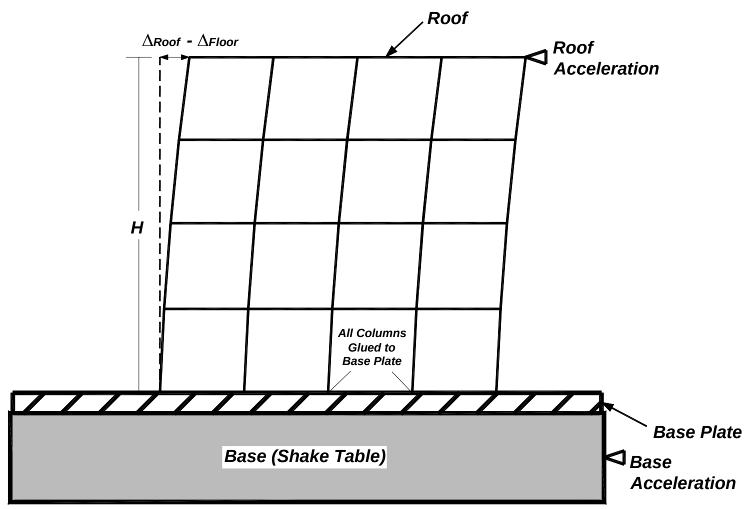


Figure 1. Acceleration response spectra for competition ground motions.

Structural analysis

During application of the base motions, accelerations are recorded at the base and roof of the structures (Figure 2) and those measurements are processed to obtain two engineering demand parameters (EDP's). The first is the peak of the absolute value of drift between the roof and the base (EDP1), and the second is the peak of the absolute value of roof acceleration (EDP2). These two EDP's were selected because they are easy to measure using the available data acquisition system and instrumentation, and to demonstrate that building fragility can depend on multiple engineering demand parameters. Displacements are computed from the measured accelerations by digitally filtering the records and subsequently double-integrating them in time.



$$EDP1 = \max\left(\left|\frac{\Delta_{Roof} - \Delta_{Base}}{H}\right|\right)$$

$$EDP2 = \max\left|RoofAcceleration\right|$$

Figure 2. Schematic of instrumentation used to compute Engineering Demand Parameters.

Damage analysis and loss analysis

Damage and loss constitute separate analyses in the PEER methodology, each carrying its own uncertainty, but the two analyses were combined in this competition and loss was represented as deterministic functions of the EDP's. Structural damage was correlated with building drift (EDP1) and damage to non-structural equipment housed inside the building was correlated with peak roof acceleration (EDP2). Cost functions relating dollar loss to the EDP's are presented in Figure 3. Similar cost functions could be developed for any number of EDP's as the competition continues to evolve.

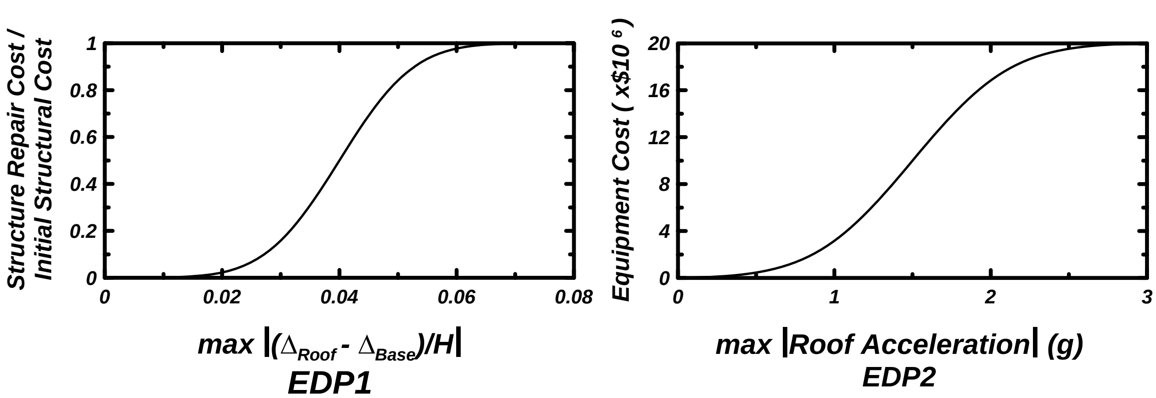


Figure 3. Cost functions relating dollar loss to Engineering Demand Parameters (EDP's).

The competition is scored based on building annual revenue, which is analogous to the decision variable (DV) in the PEER methodology. Buildings receive annual rent income based on available floor space, and additional annual income can be earned in the presentation and poster components of the competition. The initial cost of the building is the sum of the cost of land (based on building footprint area) and the initial structural cost (based on the mass of the structural components). The initial building cost is represented annually by dividing by the 100-year design life of the building. Seismic cost for each motion is computed by measuring EDP1 and EDP2 for all three earthquake motions, and computing the associated cost for each EDP for each motion using the cost functions in Figure 3. Seismic cost for each motion is represented annually by dividing by the return period of that motion, and total annual seismic cost is computed as the sum of the annual costs for each motion. Finally, annual building revenue is computed as annual rent income minus annual initial building cost minus annual seismic cost plus any additional annual revenue for high placement in the presentation and poster components of the competition and a decrease in revenue for not complying with dimensional requirements. The team with the highest annual building revenue wins the competition.

Experimental Setup and Data Acquisition

The ground motions are applied to the structures using an educational UCIST Shake Table II manufactured by Quanser (Figure 4). The table has plan-view dimensions of 457 x 457 mm (18 inch x 18 inch), a mass of 27.2 kg (60 lbf.), and can easily be transported in the trunk of a small car. The shake table operates using an electric motor, power amplifier, and WinCon control software, which interfaces with Matlab. A personal computer is required to operate the shaker. Four accelerometers can be attached to a test specimen and recorded using through the power amplifier.

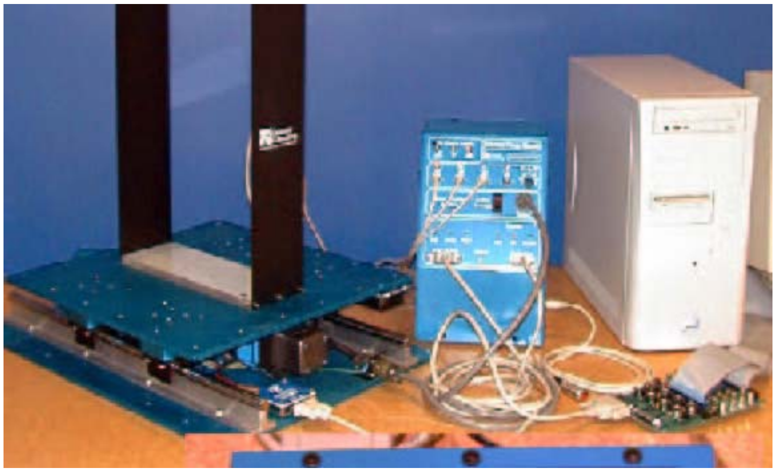


Figure 4. UCIST Shake Table II, power amplifier, personal computer, and test structure, manufactured by Quanser Consulting, Inc.

Accelerations during shaking are measured at the shake table base and at the roof of the structure, though additional accelerometers could be placed on the structure if measurement of additional EDP's were desired. Displacements are computed from each acceleration time series by performing the following steps:

1. Transfer the acceleration records into the frequency domain using a Fourier transform.
2. Digitally high-pass filter the acceleration recordings in the frequency domain using a 3^{rd} order Butterworth filter with a corner frequency of 0.8 Hz.
3. Double integrate the filtered acceleration records over time to obtain displacements.

Data processing is performed using Matlab, and outputs (time series of accelerations and displacements, and computation of structure's score) are organized into html files that are subsequently posted on the SLC website.

A portion of the low frequency range of the raw acceleration signals must be removed using a digital filter prior to double integration because the low frequency content of the signals is small compared with the noise in the signals. Highly unrealistic displacements would be obtained if the raw data were integrated in time without first filtering off some of the low frequency content. An undesired but unavoidable consequence of the filtering is that the low frequency portion of the acceleration signals, which contains permanent displacements, must be removed. As a result, the displacements computed by double-integrating the acceleration records are transient displacements; the low-frequency permanent component is not contained in the computed displacement time series.

Structural Testing

Models were fixed to a base plate with a hole pattern corresponding to the shake table. A minimum of 12 bolts were used to secure models to the shake table. Bolts were distributed throughout the base to prevent any rocking between the base plate and shake table. In the 2004 and 2005 competitions, steel threaded rods were placed at the floor levels, and hand tightened, to simulate the distribution of dead load throughout the height of the structure, as shown in Figure 6. A similar technique will be used in the 2006 competition. In the 2005 competition, a sculpture with a mass of 6.35 kg (14 lb) with an accelerometer was attached to roof level of the model, as shown in Figure 6. This sculpture will not be used in the 2006 competition.

The experimental setup for the competition is shown in Figure 5. The shake table was bolted to a heavy steel fabricated table to provide a fixed base reaction for the shake table. The operation PC, amplifier and other equipment were placed away from the direction of shaking, to prevent any damage to these items, or injury to personnel, in the event of a structural collapse. The steel fabricated sculpture and accelerometer were protected from collapse by an overhead rope line, as shown in Figure 6. This rope line had sufficient slack such that it would not interfere with the simulated earthquake motions. A model ready for testing is shown in Figure 6.

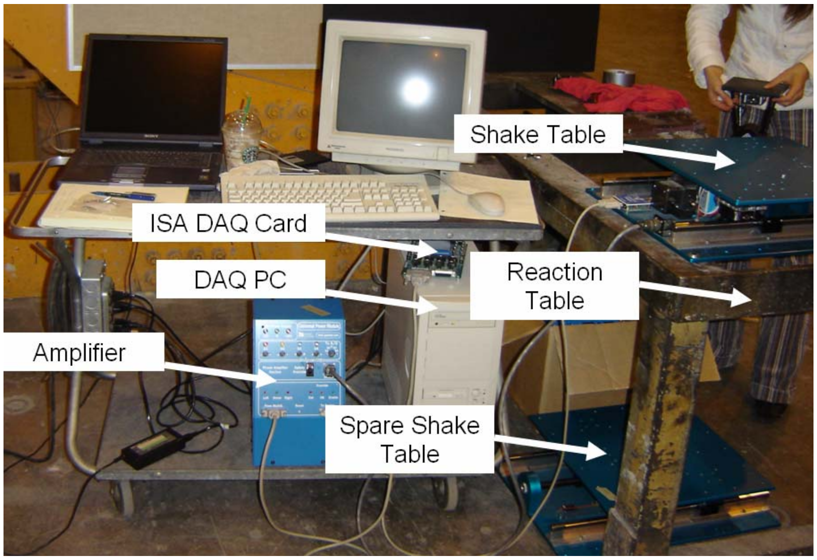


Figure 5. UCIST shake table system setup for competition.

The typical turn-around time (time to setup, test and remove a structure) ranged from 20 to 30 minutes. Setup consumed the majority of the turn-around time, and has thus been a focus for improvement. In the 2005 competition two sets of steel threaded rods were used, however, the process of placement and removal of threaded rods was still time consuming. This turn-around time can be reduced if fewer steel threaded rods were used, or if a more efficient technique of simulating dead load at floor levels was used. The turn-around time can also be reduced if all models have a proper hole pattern alignment with the shake table and with the roof sculpture. In the previous competitions, some base plates required slight correction of the hole pattern. Teams competing in the 2006 competition will be provided with the required base plates, hence ensuring a correct fit with the shake table and roof sculpture. In addition, fewer steel threaded bar weights will be used. These steps should reduce the turn-around time in the 2006 competition, which will make efficient use of everyone's time.

Figure 6. Ready for testing at the 2005 competition.

Educational Value and Outcome

The three seismic design competitions held so far have provided a unique learning opportunity for undergraduates throughout the United States. The first PEER competition was held in conjunction with the annual National Science Foundation (NSF) review of the PEER Center. This provided undergraduates the opportunity to interact with PEER graduate students and faculty. The second PEER competition was held in conjunction with the PEER Annual Meeting. This provided undergraduates the opportunity to attend a portion of the PEER meeting, and to interact with the entire PEER community. A majority of the competing undergraduates have been juniors and seniors, many of which have now continued to graduate programs in structural engineering and PEER funded research projects at the graduate level. Group photos from the 2005 and 2004 competitions are shown in Figures 7.

Results from the 2004 PEER competition are as follows:
May 12th, 2004 at the University of California, Berkeley – Richmond Field Station

First Place:	University of California, Irvine (Team 1)
Second Place (tie):	University of California, Irvine (Team 2)
	University of California, San Diego
Fourth Place:	University of California, Davis
Fifth Place:	Oregon State University

Results from the 2005 PEER competition are as follows:
April 30th, 2005 at the University of California, Berkeley – Davis Hall Structures Lab

First Place:	University of California, Davis (Team 2)
Second Place:	Florida A&M University (MCEER)
Third Place:	University of California, Berkeley
Fourth Place (tie):	Oregon State University
	University of California, Davis (Team 1)
Sixth Place:	University of Illinois, Urbana-Champaign (MAE)

Figure 7. Group Photo at the 2005 Competition (left) and 2004 (right).

Goals for Future Competitions

Financial support for the first two competitions has come from PEER. However, a new sponsor will be needed in the near future as PEER funding, from the NSF, reaches the end of its ten year duration. The initial competitions have been in a debugging phase, focusing primarily on developing the rules and requisite software tools. A second phase has been to encourage nationwide participation through the three NSF funded earthquake engineering research centers. This has been accomplished through a competition sponsored by MCEER last year, and a team sponsorship from MAE. A future sponsoring organization will determine the extent to which the competition is advanced.

References

Porter, K.A. (2003). "An Overview of PEER's Performance-Based Earthquake Engineering Methodology." *Proc. Ninth International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP9).* July 6-8, San Francisco, CA.