Webshaker: Live Internet Shake-Table Experiment for Education and Research

AHMED ELGAMAL,[1] MICHAEL FRASER,[1] DANIELE ZONTA[2]

[1]*University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0085*

[2]*University of Trento, Trento, Italy*

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ABSTRACT: Internet technologies are employed to allow real-time video monitoring, control, and execution of bench-top shake-table experiments. Structural models of relevance to education in dynamics and earthquake engineering can be tested remotely over the internet on a 24-h, 7-day (24/7) basis. The underlying elements of experiment tele-observation and tele-operation/control are incorporated in a newly developed website http://webshaker.ucsd.edu. © 2005 Wiley Periodicals, Inc. Comput Appl Eng Educ 13: 99–110, 2005; Published online in Wiley InterScience (www.interscience.wiley.com); DOI 10.1002/cae.20034

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INTRODUCTION

Earthquakes are among the most devastating natural disasters, causing loss of life and billions of dollars in damage worldwide. Currently, the effect of earthquakes on structures is a major component of research and education, in the broad areas of civil engineering and seismology, with background introductory courses in dynamics, mechanics, computational methods, random vibration, and signal processing techniques. Within these areas, laboratory and field experimentation along with computational analyses are the backbone of education.

In the realm of education, internet availability of experimental setups and related computational simulations allows for: (1) efficient use of time and resources, (2) flexibility in accessing information on a 24-h, 7-day (24/7) basis, and (3) convenience of self-paced learning with the aid of physical models [1]. Thus, the interest in developing educational websites is increasing rapidly. Among such related activities are http://flagpole.mit.edu (vibration of instrumented flagpole [2]), http://www.u.arizona.edu/~budhu/courseware.html (virtual experimentation in soil mechanics [3]), and http://octavia.ce.washington.edu/DrLayer/ (simulation of shear wave propogation in layered media [4]).

The Webshaker education/research project (http://webshaker.ucsd.edu) was initiated with the

Correspondence to A. Elgamal (elgamal@ucsd.edu).
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goal of providing a convenient learning experimental framework for applications in dynamics including introductory physics, mechanics, structural dynamics, and earthquake engineering courses. Within this framework, effort is made to actively engage students in a stimulating and informative ‘‘fun’’ educational environment. Dissemination is being facilitated through the US National Earthquake Engineering Centers (MAE, MCEER, and PEER).

The Webshaker project may be viewed as a prototype for implementation within other disciplines of engineering and science. Thus, the horizon for on-demand real-time testing is being facilitated on an unprecedented worldwide scale. Remote sharing of experimental resources and new collaboration opportunities will permeate all levels of education.

In the following sections, details of the developed website are discussed. Experience in using this website for education is summarized. Finally, plans for further developments and new applications are highlighted.

BENCH-TOP SHAKE-TABLE EXPERIMENT

The developed website (Fig. 1) allows students to conduct a shaking table test on representative simple structural models. Models are attached to the shake-table, with instrumentation installed to measure displacements and accelerations. Through the website, users can see the model and shake-table (using Windows MediaPlayer® or similar standard video streaming application), select the type and amplitude of base-shaking signal, run, and see the live shaking test take place, and view/download the corresponding recorded displacement and acceleration graphs. The recorded response may be modeled using an available numerical simulation program for comparison. Changes can be made to the input motion characteristics and a new experiment can be conducted. Students use standard internet browsers to receive video signals, conduct the visually observed experiments, and execute the associated computational simulations.

Advantages of a Web-Based Testing Facility

Compared to the conventional laboratory (lab) experience, the Webshaker remote access facility solves a series of logistical problems (restricted access to the lab, required supervision, presence of a qualified technician, etc.). In this regard, a web-based lab is available 24 h a day, allowing students to work unsupervised, at their convenience. Since the student has full control of the system, they can conduct their own ‘‘what-if’’ testing scenarios, and revisit the experiment whenever they think of new issues to explore.

As an instructional tool, the Webshaker site offers the benefits of a conventional lecture delivered in the laboratory, with the efficiency and convenience of the classroom. Thereafter, it allows students to re-run the experiment as part of their follow-up studies. As more such experiments become available over the internet, these advantages will allow both teacher and student to run and discuss a wide range of live experiments that are physically located anywhere worldwide.

EXPERIMENTAL SETUP

As mentioned earlier, the Webshaker setup consists of a structural model attached to a bench-top shake-table, and instrumented with displacement and acceleration transducers (Fig. 1). The sensors and the table are connected to a personal computer by means of an analog to digital (A/D) converter. Through a stand-alone software interface (LabVIEW VI http://ni.com/), the computer controls the input motion and the acquisition of output response. This data is displayed graphically and stored in shared directories. The computer also acts as a web-server, allowing the remote internet user access to all these functions. An attached video camera along with video streaming software transmits a live picture to the user throughout.

User Interface

Using a standard web-browser (Fig. 1), such as Internet Explorer or Netscape Navigator, users are able to:

1. Select a dynamic base excitation.
2. Operate the shake-table by clicking the ‘‘Run Experiment’’ button.
3. Download results of the experiment (i.e., acceleration and displacement time histories/response spectra recorded by the installed accelerometer and displacement transducers). The output files generated from the experiment can be viewed using a freeware Java Applet (http://ptolemy.berkeley.edu/) with zoom-in capability, or downloaded in ASCII format.
4. View a real-time streaming video of the shake-table and the mounted test structure using Windows MediaPlayer or QuickTime Player.
5. Conduct a numerical simulation of the executed experiment. The graphical result of the numerical simulation is superposed on the experimental recorded data.

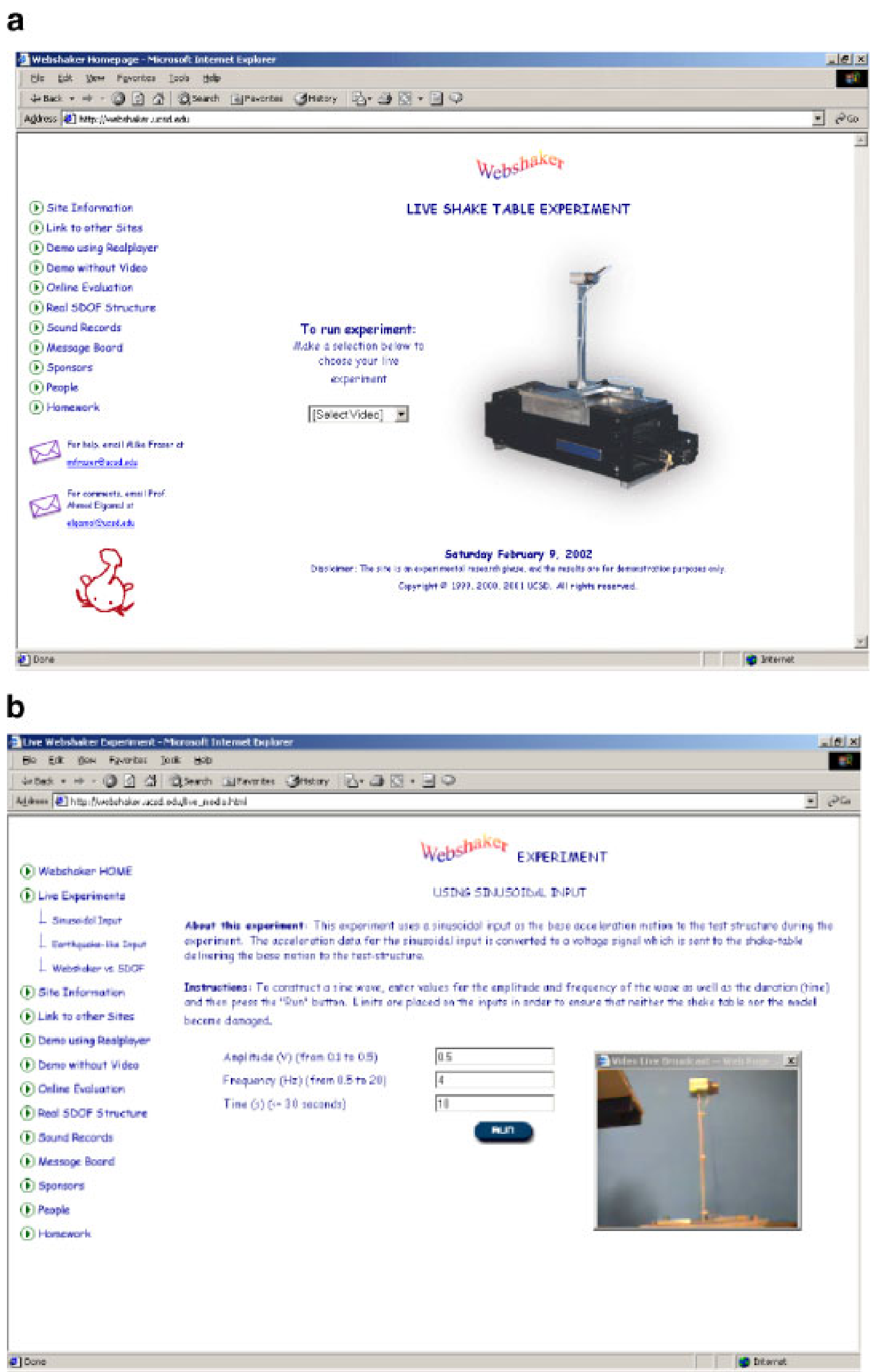


Figure 1 (a) Webshaker homepage (http://webshaker.ucsd.edu). (b) Input parameters for harmonic base excitation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Hardware Components

A bench-top uni-axial shake-table (Fig. 2) allows the reproduction of lateral ground motions. An LVDT measures the table displacement, and a laser single point sensor and an accelerometer measure the model response (Fig. 3). A camera (Fig. 3) equipped with a video capture card allows for transmitting a live picture of the model response.

Software Components

The employed server computer is a PC running Microsoft Windows NT Server 4.0. A multi-tasking

Figure 2 APS Model 113-HF shake-table. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

environment with HTML and Perl scripts [5] allows the different functions to be executed at the same time, as schematically represented in Figure 4. A pooling scheme allows up to five users to conduct independent experiments and store their results simultaneously. This procedure consists of assigning a priority to user requests, based on the order in which they are received.

An important aspect in the Webshaker setup was the development of a robust system providing the necessary reliability required for 24/7 operation. In the early stages of development, this required an extensive phase of error checking and debugging. During this time, the website was only used on a limited basis and problems were corrected as they were encountered. Currently, the website runs reliably with minimal maintenance. The Webmaster expends approximately a half-day per week for such maintenance, including backups after any modifications or additions.

Video Streaming

In addition to the displacement and acceleration transducers, a digital video camera allows for visually monitoring the shaking test. Standard computer cameras (such as the one used here) can capture as many as 30 frames per second, with a 512×492 effective pixel resolution (in the current configuration this corresponds to about 2 mm spatial resolution).

Using video-streaming technology, the live video signal can be sent to a remote user essentially in real-time. Commercial video-streaming technologies (e.g., Quicktime http://www.apple.com/quicktime/ or Microsoft Windows MediaPlayer http://www.microsoft.com/windows/mediaplayer) allow for transmitting the best possible signal using the limited available internet bandwidth.

Execution of Experiments

Following the server request, LabVIEW uses the PCI-MIO board (Fig. 3) as an interface to drive the shake-table and to acquire signals from the instrumentation. There are two types of base motion available for experiments: (1) harmonic and (2) earthquake-like motions.

For the harmonic motion, the user specifies amplitude, frequency (Hz), and duration (second) of a sine wave excitation (Fig. 1b). Once the user has specified the sine wave characteristics, LabVIEW converts the signal into a series of discrete points with a voltage for each time step. Currently, acceptable values of frequency range from 0.5 to 20 Hz, encompassing the range of interest for earthquake engineering applications.

The other form of input signal is an earthquake-like motion (Fig. 5a). These motions are constructed by scaling selected acceleration records from historic events, such as the 1994 Northridge earthquake, among many others (Fig. 5b).

Upon clicking the "Run Experiment" button, the user-selected dynamic base excitation is sent to the server. Perl scripts generate an input file with the parameters specified by the user. This file is transmitted to LabVIEW, which constructs and sends the corresponding input voltage signal to the shake-table. While the shake-table is running, LabVIEW simultaneously acquires data from the sensors. The analog signals from the sensors are sampled and digitized at 200 samples per second by the data acquisition card. Finally, the digitized output data streams are converted to displacements/accelerations.

LabVIEW also performs some basic signal processing functions in both the time-domain (e.g., filtering) and frequency-domain (e.g., Fourier analysis, Fig. 6a), with the results sent back in ASCII format. These data files are then sent to the user's remote computer, where *Ptolemy* (http://ptolemy.eecs.berkeley.edu), a Java applet embedded in the HTML, processes and produces graphical representations of the data on the user's browser (Fig. 6b). This graphical output is also available for inclusion in a report or homework assignment.

Numerical Simulation

A numerical simulation can be performed along with the live experiment, to compare the actual and predicted responses of the model. This simulation computes the response of a single-degree-of-freedom (SDOF) linear model, subjected to a known base acceleration, using the classical Newmark predictor multi-corrector algorithm for the average acceleration case [6,7]. The governing equation is of the form $\ddot{x} + 2\zeta\omega\dot{x} + \omega^2 x = -\ddot{u}_g$, where ζ is viscous damping ratio, ω is natural frequency, $\ddot{x}$, $\dot{x}$, x are acceleration, velocity, and displacement of the model relative to the

Figure 3 (a) Macro sensors DC 750-3000 LVDT. (b) Laser Measurement International SPR-04 single point sensor. (c) PCB Model 3701 accelerometer. (d) National Instruments PCI-MIO data acquisition card. (e) EyeCom Pro 9600 camera. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

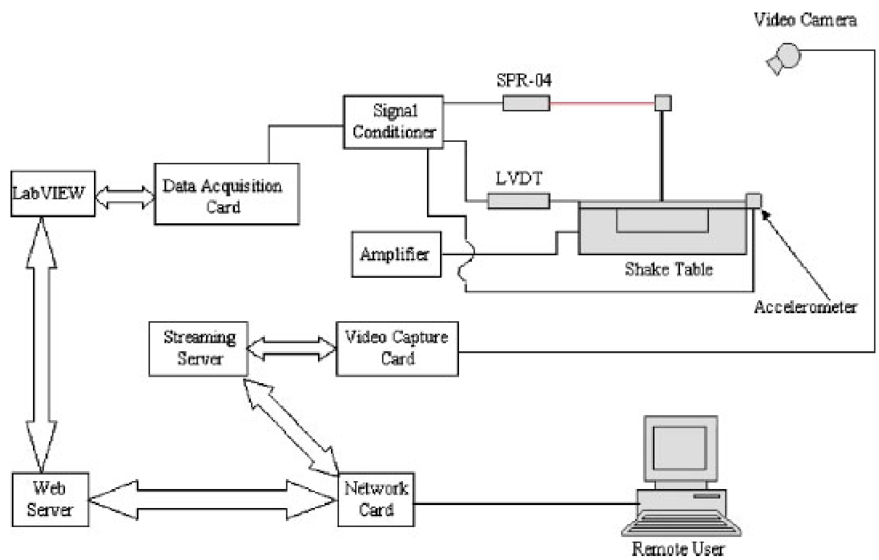


Figure 4 Schematic of the Webshaker site. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

base, and $\ddot{u}_g$ is the ground acceleration (shake-table acceleration). The recorded shake-table acceleration is used as an input, and the computed model response $(\ddot{x},\ \dot{x},\ x)$ is returned. Users specify values of damping ratio ζ and natural frequency ω in the numerical model. The actual dynamic properties may be identified by varying these parameters, to minimize the difference between the computed and recorded response (Fig. 7).

Structural Models

The facility was designed to operate with different models. The model shown in Figure 8a consists of an SDOF aluminum inverted pendulum bolted to the shake-table (used to represent the response of a single-story building). As mentioned earlier, the base and model motions are monitored by LVDT, accelerometer, and a laser displacement transducer (Fig. 3). Alternate models for the table include single and multi-story aluminum frames. An example of these models is the two-story frame shown in Figure 8b (along with a SDOF model as well). This model was conceived and actually built as part of a class project for the undergraduate earthquake engineering course at UCSD. With these two models, a number of fundamental dynamic principles can be demonstrated (see Appendix).

MAIN EDUCATIONAL GOALS

In the development of this facility, we aspired to enhance the traditional educational process. Among the main objectives were:

- Motivating students by facilitating a convenient unsupervised self-learning environment.
- Fostering a versatile environment for collaboration and interaction within the classroom, in the form of classroom projects.
- Bringing elements of the research testing experience right into the classroom. Generally, this experience is currently often studied ‘‘second-hand,’’ through published technical articles and textbook reports.
- Allowing otherwise effort-intensive experiments to be executed routinely for research/educational purposes.
- Working towards development of courses with experimentation content that can be effectively delivered offsite, greatly enhancing the educational experience [8].

Webshaker as a Teaching Tool

During a lecture, an instructor may be presenting material of relevance to the Webshaker testing experience. Within this lecture, the practical aspects of a concept (such as ‘‘phase lag’’ which is usually introduced through mathematical terminology and complex algebra), can be readily shown by running a series of experiments and discussing the results. In this context, student questions can be addressed with experimental evidence, rather than solely with mathematical considerations. Thus, the instructor has the opportunity to ‘‘visit the lab,’’ while in the classroom covering a variety of topics such as time/frequency-domain dynamic response, Fourier analy-

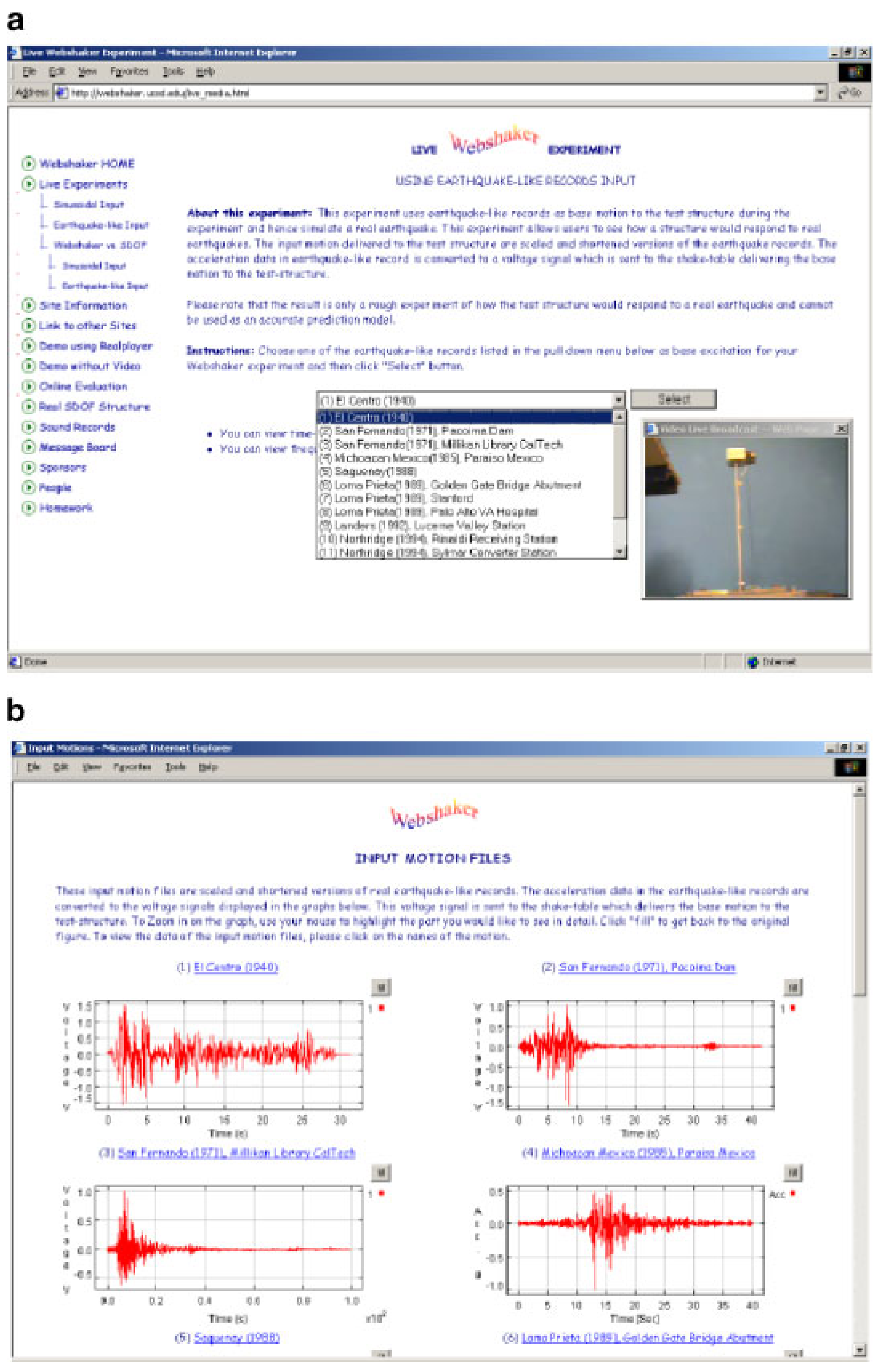


Figure 5 (a) Earthquake-like base excitation. (b) Time history plots of four of the available earthquake-like motions. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

sis, and numerical (time) integration. In this regard, exercises related to each of these topics are already available to the teacher on the website (http://webshaker.ucsd.edu/homework180.html). Instructors (or students on their own) have the opportunity to use these exercises and guide students through the material by utilizing this experimental setup.

INSTRUCTIONAL EXPERIENCE

In our earthquake engineering courses at UC San Diego (UCSD), Webshaker is already being utilized. For instance, in an exercise focused on the concept of resonance, students are asked to identify the dynamic parameters of the Webshaker model using two

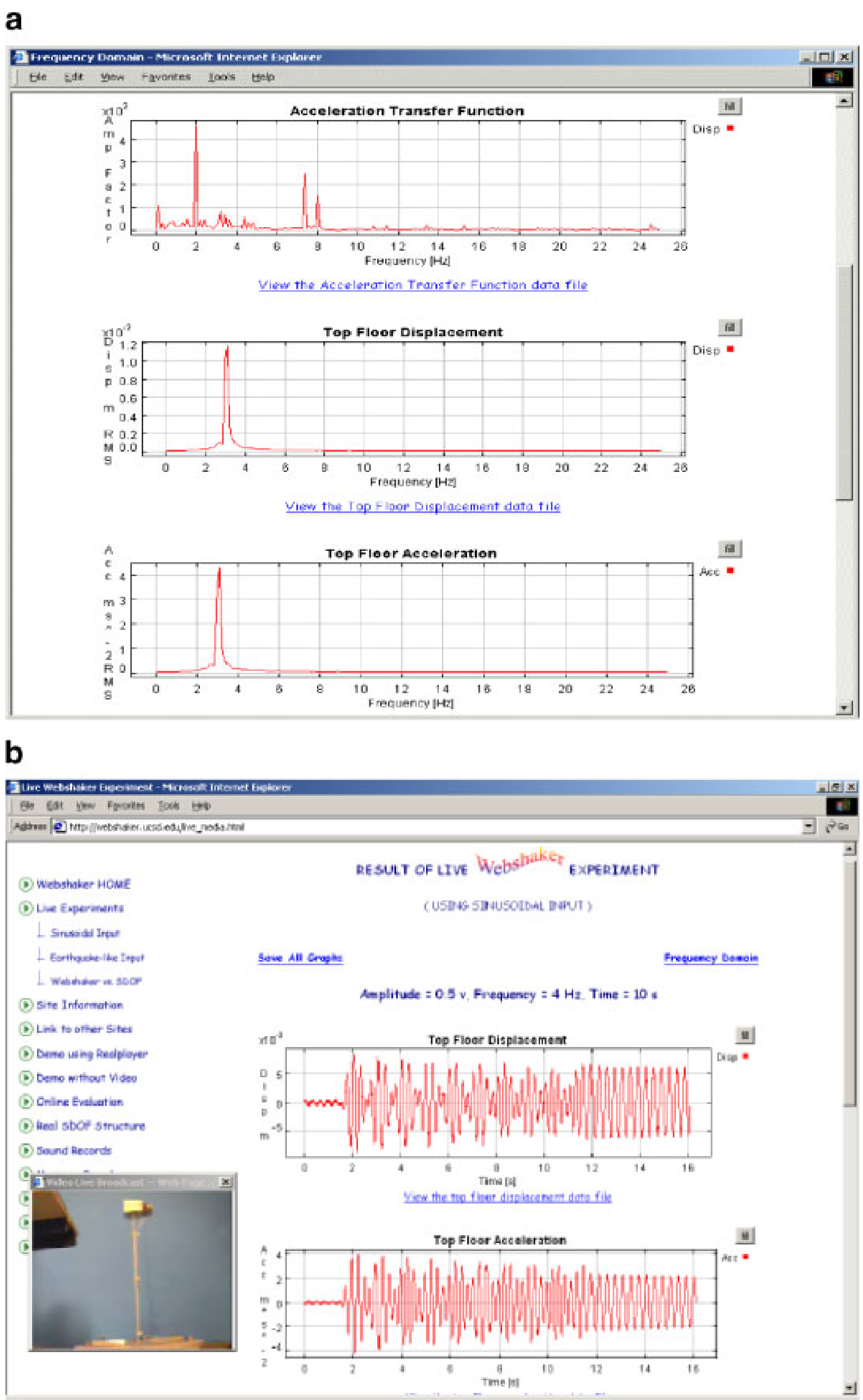


Figure 6 (a) Frequency-domain form of recorded data and acceleration transfer function. (b) Graphical representation of recorded data. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

different experimental approaches: (1) by analyzing the free-vibration response of the model in the time-domain and (2) through inspection of resonance in the frequency-response function [9]. They are asked to compare the results and discuss their findings. This last step represents a self-check regarding reliability of the outcomes. Should a contradiction arise, the student can go back and re-run the experiment to verify the findings. As opposed to an assignment based solely on theory, students deal with the response

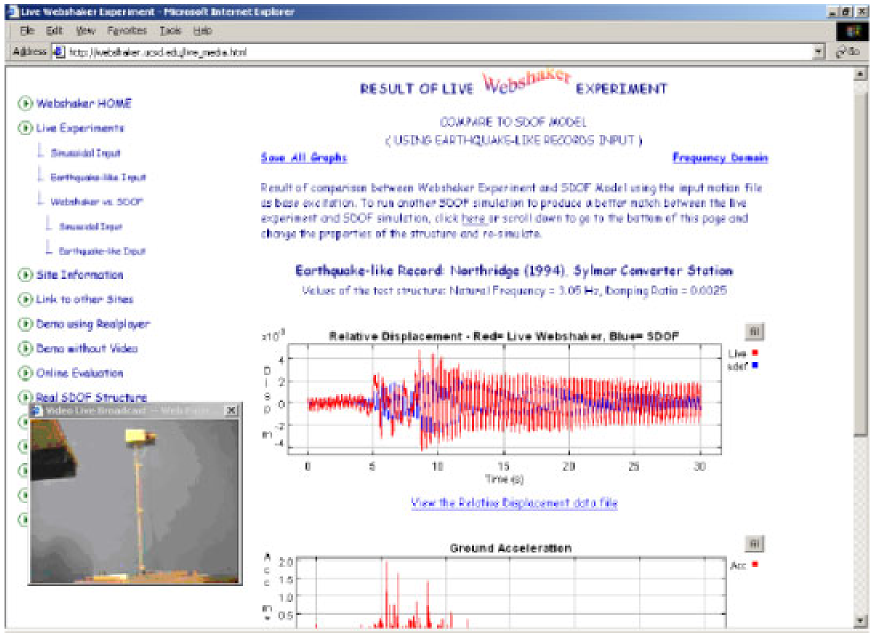


Figure 7 Comparison between recorded data and numerical modeling. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

of an actual physical structure (similar to practical engineering situations).

Education Assessment

A professional online evaluation form was developed, and is now available at the Webshaker site (http://webshaker.ucsd.edu/survey.html). The evaluation form is composed of two parts. Part 1 is intended to gather background information (before using Webshaker), including year of enrollment, related introductory classes, web-access location and connection speed, and familiarity with experimental testing procedures and the World Wide Web. Part 2 assesses quality of the site and asks students to rate their experience. This includes technical specifics such as the web-interface aesthetics, convenience, quality, and benefits of video streaming. In addition, students are encouraged to provide their own comments concerning the educational content.

The two evaluation forms (parts 1 and 2) may be completed and submitted online. This formal student feedback (as we collect and compile it) will be most effective in future upgrades of the overall Webshaker site framework. Moreover, it will provide insight for developers of other internet-based educational tools.

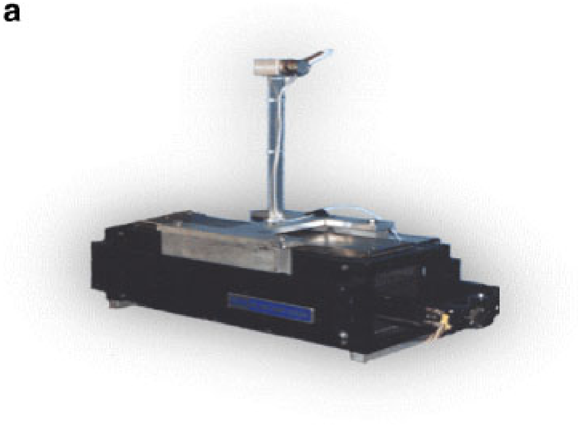
DISSEMINATION

It is recognized that dissemination and wide adoption represents a major component of this Webshaker effort. While the internet itself is a most effective medium, plans have been drawn for broader dissemination at the state level first and eventually nationally and internationally. Within California, instructors at UCSD, Caltech, UC Davis, and UC Irvine are being approached to include Webshaker applications in their dynamics/earthquake engineering courses. On the national scene, dissemination efforts will be undertaken through the three NSF funded national earthquake centers (MAE, MCEER, and PEER). In addition, effort is underway for using Webshaker in lower level engineering courses (physics and mechanics courses), as well as other upper level undergraduate and graduate courses in civil and mechanical engineering (e.g., vibrations, structural dynamics).

ADDITIONAL FEATURES

The Webshaker site now hosts an online collection of sound recordings taken from historical earthquakes [10]. These sound records are intended to give students a realistic impression of people experiencing an earthquake.

Finally, a compiled select set of links to "other earthquake-related websites," allows users to conveniently delve deeper into the world of earthquakes, rendering the most valuable internet resources at their fingertips (information, earthquake re-connaissance photographs, recorded earthquake motion databases a



b

Figure 8 (a) Aluminum single-degree-of-freedom inverted pendulum model. (b) Two-story aluminum frame model. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

worldwide, educational materials, earthquakes in the news, documentaries, and so forth).

RELATED WEBSHAKER DEVELOPMENTS

Additional structural models for testing using Webshaker are a most valuable addition. If these models are conceived/built by the student (or the class), the educational experience is further personalized and much enhanced (because students test their own model). In fact, the two-story model of Figure 8b was designed and built as a class project, and the testing experience was found to be most rewarding for all.

On a parallel track, an internet framework is being developed for conducting vibration tests on actual structures. Currently, this includes a UCSD pedestrian cable-stayed bridge and the Millikan Library at Caltech (collaborative effort with Professor James Beck). The Millikan Library is a nine-story reinforced-concrete structure, which has been the focus of much research during the last 30 years [11–13]. It is currently instrumented with a 36-channel monitoring system capable of recording ambient as well as strong-motion during earthquakes. Real-time test data from the monitoring system will be available through the internet web-based graphical interface, along with appropriate analysis exercises.

SUMMARY AND CONCLUSIONS

Internet web-based technologies are employed to allow for real-time video monitoring, control, and execution of bench-top shake-table experiments. The effort attempts to actively engage students in a stimulating and informative ‘‘fun’’ educational environment. Simple structural models of relevance to education in dynamics and earthquake engineering can be tested remotely over the internet at http://webshaker.ucsd.edu.

Elements of the developed internet website were presented and discussed. Experience in using this website for education was summarized, and plans for further developments and new applications were highlighted. Dissemination is being facilitated through the National Earthquake Engineering Centers (MAE, MCEER, and PEER).

The Webshaker project may be viewed as a prototype for implementation within other disciplines of engineering and science. Thus, the horizon for on-demand real-time testing is becoming a reality on an unprecedented worldwide scale.

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APPENDIX: WEBSHAKER EXERCISES

In order to complement the online testing capability, instructional material has been prepared and made available through the website (http://webshaker.ucsd.edu/homework180.html). This material includes demonstrations aimed at investigating the salient dynamic response characteristics of the models, sample exercises, and a class project.

Two sample exercises were prepared specifically for use with the Webshaker facility. Within the first exercise, students estimate natural frequency of a SDOF structure from the recorded free-vibration time histories (as well as from frequency-domain representation of this data), investigate the "beating" response phenomenon [14], and compare the recorded response from earthquake-like base motions to the results of a numerical simulation.

The second exercise is concerned with vibration of the two-degree-of-freedom system (Fig. 8b). In this exercise, students determine the model natural frequencies by inspecting the frequency-domain output. Shaking the model harmonically at each natural frequency and recording the relative displacement of each floor, mode shapes of the model may be identified. Once the resonant frequencies and mode shapes have been determined, students are asked to describe the steps involved in obtaining a modal solution for base earthquake excitation. Using an available input earthquake motion, students may then shake the model and compare the response to a corresponding numerical prediction.

In addition to the above-mentioned exercises, a class project has been created to allow students the opportunity to design their own models. The models must satisfy specified masses and stiffness requirements such that the structure resonates at given fundamental frequencies. As part of the project, a comprehensive guideline document was prepared and made available on the website, to aid students in each step of the design and analysis phase. The exercise begins with setting up the equation of motion in matrix form, and if necessary performing static condensation to remove zero mass degrees of freedom. Next, the Eigen-value problem is solved to determine the unknown design parameters. Based on the calculations, a model is constructed and tested on the shake-table to verify the underlying calculations. Thereafter, an earthquake response simulation is conducted experimentally and numerically and the results are compared (for a series of different earthquake records). The numerical prediction is performed by a spreadsheet that implements modal analysis and the Newmark time integration scheme [6,7].

It was found that models conceived/built by the students, were effective in enhancing the educational experience. Many students were happy to spend the extra time building such models, and follow-up with a comprehensive lab report, and a 15 min PowerPoint presentation. In fact, the two-story model of Figure 8b was actually built as a class project, and the testing experience was found to be most rewarding for all.

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BIOGRAPHIES

Ahmed Elgamal is currently serving as chair of the Department of Structural Engineering. He is an expert in earthquake engineering and computational geomechanics. Incorporation of information technologies into structural engineering is one of his main research areas. Internet applications include sensor networks for monitoring our civil infrastructure, with real-time condition assessment and decision-making algorithms (http://healthmonitoring.ucsd.edu). Integration of research and education with live web-accessible experiments is a main interest (http://webshaker.ucsd.edu).

Michael Fraser received his bachelor of science and master of science degrees in structural engineering from the University of California, San Diego, where he is currently nearing completion of his PhD. His thesis is focused on the development of an integrated framework for structural health monitoring. His research interests include data/image acquisition, database systems, image processing and computer vision, damage detection, and data fusion (http://healthmonitoring.ucsd.edu).

Daniele Zonta is an assistant professor in the Department of Mechanical and Structural Engineering at the University of Trento. He completed his bachelor of science and master of science degrees at the University of Padova, Italy, in 1996, and in 2000 he received his doctorate degree from the University of Bologna, Italy. His fields of research include structural health monitoring and control, information technologies for real-time safety assessment, and structural identification and damage localization.