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Full-scale Mechanical Vibrations Laboratory

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Abstract

A unique full-scale experimental laboratory was recently developed to improve students' physical understanding of the complex principles presented in mechanical vibrations courses. Rather than creating the typical small scale model with lumped masses to illustrate important mechanical vibrations concepts, a full-scale structure was used to improve the relevance of the experiments so that students can more readily connect the results with the real world. The Bridge House, a one-story building constructed by undergraduate students, is aptly named since it spans a small seasonal creek in the student outdoor experimental construction laboratory located on the California Polytechnic State University, San Luis Obispo (Cal Poly) campus. This structure is ideal for vibration experimentation since it is simple enough for the students to quickly model with hand calculations and computational models, yet complex enough so that the results can be readily applied to an actual structure. Forced vibration testing was employed to excite the building. The goal of the forced vibration testing was to experimentally determine the building's natural frequencies, mode shapes, and damping so that the students could compare their predictions of the dynamic response of the building.

Two experiments were conducted by the students, a vertical floor forced vibration test where the shaker was placed vertically at the midpoint and at the quarter points along the Bridge House floor, and a lateral roof forced vibration test where the shaker was mounted to the underside of the central roof beam. The vertical floor vibration experiment allowed students to physically feel the difference between mode shapes by walking along the floor and experiencing maximum vertical excitation at the peaks as well as minimal vertical excitation at the nodes. The lateral roof vibration experiment provided a basis for the students to compare their hand calculations and computational model predictions of the dynamic response of the structure. Prior to conducting the lateral roof vibration experiments the students' computational model predictions of the Bridge House response varied widely. By comparing their predictions to the forced vibration testing, the computational models improved, narrowing the range of fundamental frequencies reported by the students; consequently, a healthy skepticism for the computational results was forged in the students' minds.

Introduction

A unique full-scale experimental laboratory was recently developed to improve students' physical understanding of the complex principles presented in mechanical vibrations courses. Although helpful, there is often a disconnect in student's minds between simplified models and real world applications. Even with scaled physical models, concepts such as eigenvalues, instability, and time constants often remain mysterious to students[1]. Rather than creating the typical small scale model with lumped masses to illustrate important mechanical vibrations concepts, a full-scale structure was used to improve the relevance of the experiments so that students can more readily connect the results with the real world. In an effort to improve student learning in structural dynamics, forced vibration testing[2,3,4] of buildings on the Cal Poly campus has been conducted.

The Bridge House, a one-story building spanning a small seasonal creek, was constructed in 1966[5] by undergraduate students in the Cal Poly outdoor experimental construction laboratory. The goal of the project was to create a structure that utilized the rough terrain of the nine acre canyon (see Figure 1). The building has served many purposes over the years including housing for the canyon caretaker. The Bridge House was recently transformed by undergraduate students[6] into a structural dynamics laboratory, including aesthetic rehabilitation, fabrication and installation of testing equipment and the addition of removable braces to alter the building dynamic response. The Bridge House is ideal for vibration experimentation since it is simple enough for the students to quickly model by hand calculations and with computational models, yet complex enough so that the results can be readily applied to an actual structure. The structural system is straightforward consisting of ordinary moment frames in the N/S direction, and concentrically braced frames in the E/W direction. Removable braces were also installed in the E/W direction (see Figure 1c) so that the influence of the braces on the dynamic response of the structure could be studied, however, these braces were not engaged in this laboratory experiment. The concrete piers support the structure at the four corners (see Figure 1d). Key concepts such as resonance, damping, modal participation, natural frequencies and mode shapes

(a) (b)

(c) (d)

Figure 1. Bridge House (a) Exterior; (b) Interior; (c) Removable Brace Connection (N/S Direction); (d) Concrete Foundation Piers

all come to life when the full-scale structure is excited.

Student Vibration Laboratory

The vibration laboratory challenges students to assess the Bridge House dynamic response through multiple avenues:

1) Hand calculations
2) Computational models
3) Site visit, Forced Vibration Testing
4) Post-Experiment evaluation of computational models

Students began by performing hand calculations based on the Bridge House drawings to estimate the building natural frequencies and mode shapes to provide a reality check for the computational model. Multiple modeling decisions ensued, challenging students to consider a variety of issues related to design, construction and building behavior. The first issue for the students to address was the building weight. The roof diaphragm is comprised of rigid insulation topped with gravel over a corrugated steel metal deck. The floor diaphragm is composed of a 3½ inch thick lightweight concrete over a corrugated steel metal deck. The student estimates of the roof diaphragm weight ranged from 21.7 psf to 50 psf, a wide range considering the simplicity of the structure. The weight of the roof was later measured to be 30 psf. Students were also faced with modeling choices related to the building stiffness such as how to model member connections, rigid end zones, boundary conditions, built-up column sections, and the effective story height. (see Figure 2).


(a) (b) (c)

Figure 2. (a) Member Connections; (b) Boundary Conditions; (c) Plan View of Built-up Columns

Next students created computational models of the Bridge House based solely on the structural drawings. Students were given the choice of using either RISA 3D[7] or ETABS[8]. A typical computational model is shown in Figure 3. The student predictions of the fundamental frequency in the N/S direction (moment frames) ranged from 0.5 hz to 3.5 hz, with an averag of 2.7 hz, all below the experimentally determined frequency of 4.5 hz. Reasons for the low prediction of the natural frequency ranged from high weight predictions to innaccurate modeling of the built-up column sections, inaccurate story heights and lack of rigid ends zones modeling the depth of the roof.

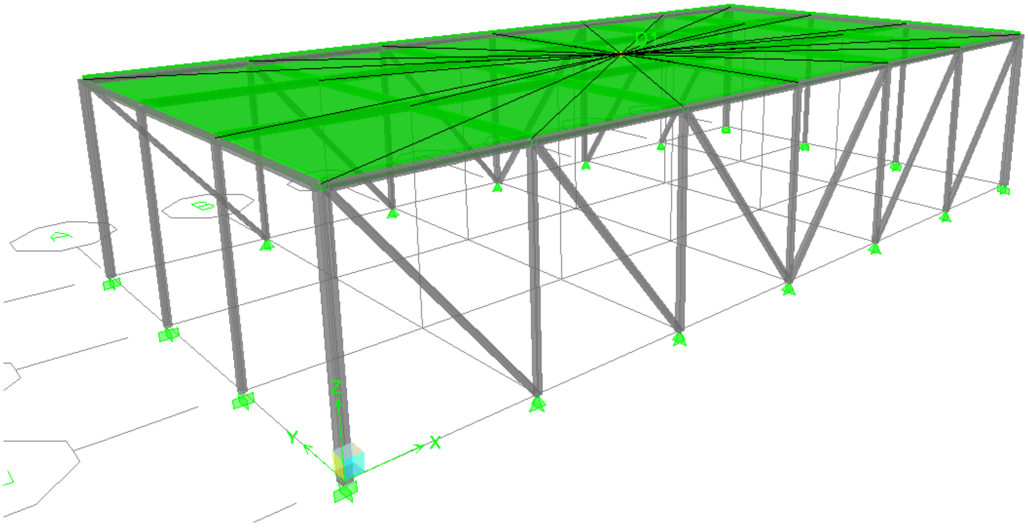


Figure 3. Typical Student Computational Model

The next step in the labratory was a site visit by the students and forced vibration experimentation (see Figure 4). The Bridge House site is a 10-15 minute walk from the center of campus. Prior to the experiment students were given the opportunity to inspect the structure upclose and determine if their pre-test modeling assumptions were reasonable. Students began to realize that some of their modeling assumptions were inaccurate. Students setup the forced vibration experiment on their own including simple tasks such as starting the generator to more complex tasks such as mounting the equipment and managing the data acquisition system (see Figure 5).

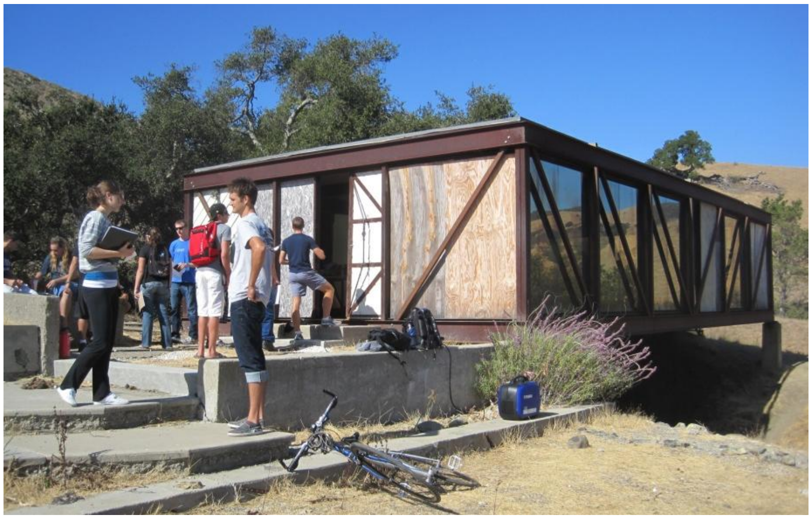
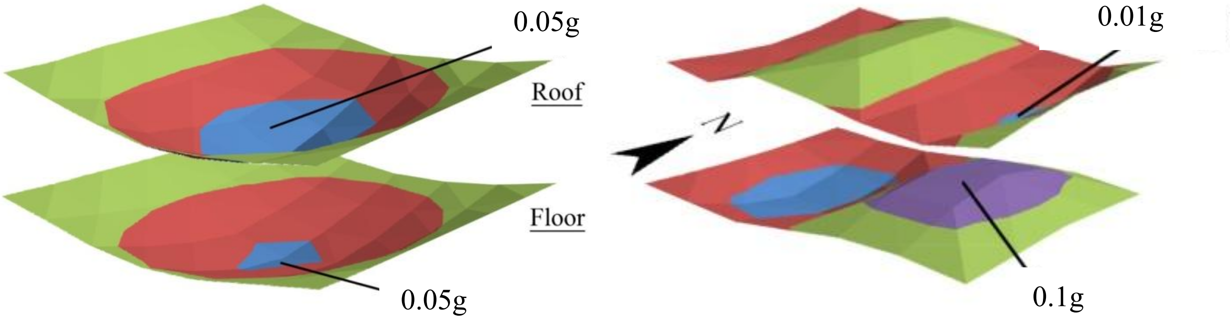


Figure 4. Student Site Visit and Forced Vibration Experimentation

The students physically experienced the vertical vibration experiment due to the 48 ft. span of the floor diaphragm, serving as a bridge across the seasonal creek. With small scale shakers most accelerations in buildings are below the level of human perception, thus the use of micro-g accelerometers is common. However, the vertical vibrations in this bridge-like structure rose to the level of 0.1g. Isometric illustrations of the 1st and 4th experimentally measured vertical modes are shown below in Figure 6. During the first vertical mode the max accelerations occurred at the center of the floor diaphragm while the accelerations at the center of the floor diaphragm were nearly zero for the 4th vertical mode.


(a) (b) (c)

Figure 5. Student Setup of (a) Roof Mounted Horizontal Shaker; (b) Floor Mounted Vertical Shaker; (c) Roof Mounted Accelerometers



(a) (b)

Figure 6. (a) 1st Vertical Mode of Vibration; (b) 4th Vertical Mode of Vibration[9]

The most exciting part of the experiment for the students was feeling the vertical floor vibrations when resonance was reached. This is the key advantage of forced vibration testing of the Bridge House versus larger structures on campus. The students placed the accelerometers and the shaker in the vertical position at the quarter point of the floor diaphragm (see Figure 5b). Figure 7 shows the students experiencing minimal accelerations at the center of the floor and maximum accelerations at the quarter points for the 4th vertical mode. The students were astute enough to ask whether their own mass would alter the building natural frequencies! They were able to experimentally validate this to be true; as a result, the students limited the number of people walking across the floor at one time to five people. The students clearly enjoy the dynamics experimentation. The challenging mathematics and physics that govern mechanical vibrations are brought to life in an exciting way, leading to improved student learning and interest.

Figure 7. Students Experiencing Vertical Mode Shapes for the 4th Vertical Mode

Next, the students shook the building laterally to determine the natural frequency in the N/S direction (moment frame direction). The shaker and accelerometers were mounted to the underside of the roof diaphragm beam at the center of the structure (see Figure 5a,c). The students varied the frequency until the accelerations were maximized at 4.5 Hz.

Post-Experiment Student Computational Analysis

After experiencing the building vibrations firsthand the students were eager to improve their pre-test models of the Bridge House. The students had trouble accurately estimating weight of the rigid insulation topped with gravel on the roof diaphragm, fortunately a graduate student conducting research on the structure cut out and weighted a 1 ft. x 1 ft. section of the roof to validate the weight (see Figure 8). The 1 ft x 1 ft square of 5 ply sheathing, gravel and rigid insulation weighed 15 lbs, equivalent to 15 psf[9]. The total roof weight was estimated to be 30 psf. Armed with a more accurate assessment of the building weight and improved estimates of the member connections, boundary conditions and built-up section properties, the students revised their computational models, the post-test student predictions of the fundamental frequency in the N/S direction (moment frames) ranged from 1.5 hz to 5.5 hz, with an average of 4.0 hz. This was an improvement from the pre-test average of 2.7 hz and closer to the experimentally determined frequency of 4.5 hz (see Figure 9). A wide range of frequency predictions remained due to the students' attempt to model the roof diaphragm as semi-rigid based on the roof flexibility measured in the E-W direction (braced Frame direction) during the forced vibration testing. Moving from a rigid diaphragm to a semi-rigid diaphragm dramatically complicates the model, increasing the required degrees-of-freedom from three to hundreds of degrees-of-freedom. As a result, the students learned an important lesson about the value of model simplicity.

Figure 8. Bridge House Roof Weight Verification[9]

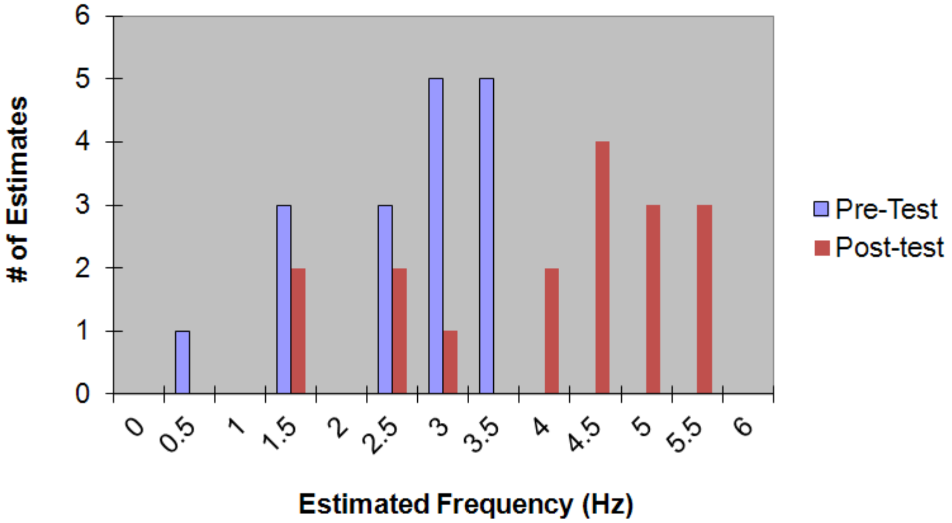


Figure 9. Student Pre- and Post-Experiment Computational Model Prediction of the Bridge House N/S Direction Fundamental Frequency

In addition to improved predictions of the dynamic response of the Bridge House, student exam results assessing key concepts in mechanical vibrations rose from an average of 72% the previous two years to 83% once the Bridge House experimental laboratory was introduced.

Additional assessment of student learning resulting from the full-scale mechanical vibrations laboratory including retention of key mechanical vibrations principles will be conducted this year.

Conclusion

Student led forced vibration experimentation of real structures significantly enhances student learning and interest of mechanical vibrations. The Bridge House, a one-story building spanning a small seasonal creek in the student outdoor experimental construction laboratory located on the Cal Poly campus is an ideal structure for vibration experimentation. This structure is simple enough for the students to quickly model with hand calculations and computational models, yet complex enough so that the results can be readily applied to an actual structure. The goal of the forced vibration testing was to experimentally determine the building's natural frequencies and mode shapes so that the students could compare their hand calculation and computational model predictions of the dynamic response of the building.

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