AC 2009-964: DEVELOPING A FEEL FOR STRUCTURAL BEHAVIOR

Cole McDaniel, California Polytechnic State University, San Luis Obispo

Graham Archer, California Polytechnic State University, San Luis Obispo

Developing a 'Feel' for Structural Behavior

Current approaches to engineering education have failed to prepare students to use computers in engineering applications. Upon graduation, engineering students are often not able to create a sufficiently accurate computational model of the systems they design and analyze. Unfortunately this is the very task that many young engineers are asked to perform soon after they embark on a career in engineering. Recent articles and surveys of practicing engineers have highlighted disappointment with the confidence young engineers have in computer analysis results. "With the increased use of the computer, we seem to have gotten lazy about asking the next question. If the printout says something is so, it must be so" [3]. This lack of skepticism with computer analysis results spans engineering disciplines from bioengineering to aerospace engineering. Despite the call by both engineers and academia for improved education in the area of modeling structural system behavior, significant progress has not been made. Why has the progress been so slow? Accurately modeling the behavior of engineered systems with computer software requires the engineer to understand the phenomena they are modeling in order to accurately develop the model in the first place. Developing this knowledge is a life-long endeavor; however, the foundation needs to be laid in the undergraduate education. This foundation can most effectively begin through student led experimentation of real engineered systems.

Innovative engineering curricula are needed to challenge students to ask the thought provoking questions needed to arrive at a logical solution on the computer such as "why should I choose that option?", "what is the basis for that assumption?" "how can I verify the accuracy of the output?...". As computers gain computational speed and more of engineering design and analysis becomes automated, students will become further challenged to calibrate their models and check the accuracy of the results. "Even though information technology is a powerful reality, an indispensable, rapidly developing, empowering tool, computers do not contain the essence of teaching and learning, which are deeply human activities. So we have to keep our means and ends straight" [4]. With the inevitable increase in the use of computers in engineering applications, a solution to this problem of inaccurate modeling is quickly needed.

A unique laboratory exercise was recently developed to address the problem of inaccurate modeling. Senior undergraduate students in their terminal analysis course were challenged with the task of predicting the natural periods of vibration of a building on campus using computer software and then comparing their results to those from ambient vibration tests performed by the students themselves. Correctly predicting the natural periods of vibration is an excellent metric of the accuracy of the analytical model. Since the building is located on campus, students were able to visit the building and see first hand the structure they modeled.

Laboratory Description

The campus building selected for this exercise was the newly constructed Construction Management faculty-office/classroom structure (see figure 1). The building is a three-story concentrically-braced steel-frame structure with glass and precast concrete exterior curtain walls. The floors and roof consist of a 3-inch concrete topping on a corrugated steel deck. The building footprint is approximately 82 feet by 99 feet. The building was selected for several reasons: 1) the building is on-campus and is easily accessed by the students; 2) the structural plans for the building were readily available to the students to aid in structural member properties and load takeoff calculations; 3) the original design engineers were available for consultation; and 4) the lateral resisting system (braced frames) was visible and obvious.

Figure 1: The Building

A typical analytical model created by the students is shown in figure 2. To reduce the workload for the students, they were permitted to make a few simplifying assumptions:

1) A small number of gravity columns were purposely placed outside the typical grid layout. Since these variances do not affect the lateral motions of the structure, the students were permitted to place the columns on the grid.
2) The stairwell consists of a substantial reinforced concrete wall with cantilevered stairs and platforms which is structurally isolated from the building. The students were instructed not to include the stairwell in their model.
3) The students were instructed to ignore the building basement in the lateral analysis.
4) The floors and roof were assumed to act as a rigid diaphragm. The missing in-plane flexibility will slightly affect the student's predictions. However this was considered acceptable.
5) A small bridge is integral to the structure to provide access to the adjacent building. The students were permitted to ignore the bridge as long as the mass of the bridge was included in their models.
6) Small openings and irregularities in the floor slabs were permitted to be ignored.

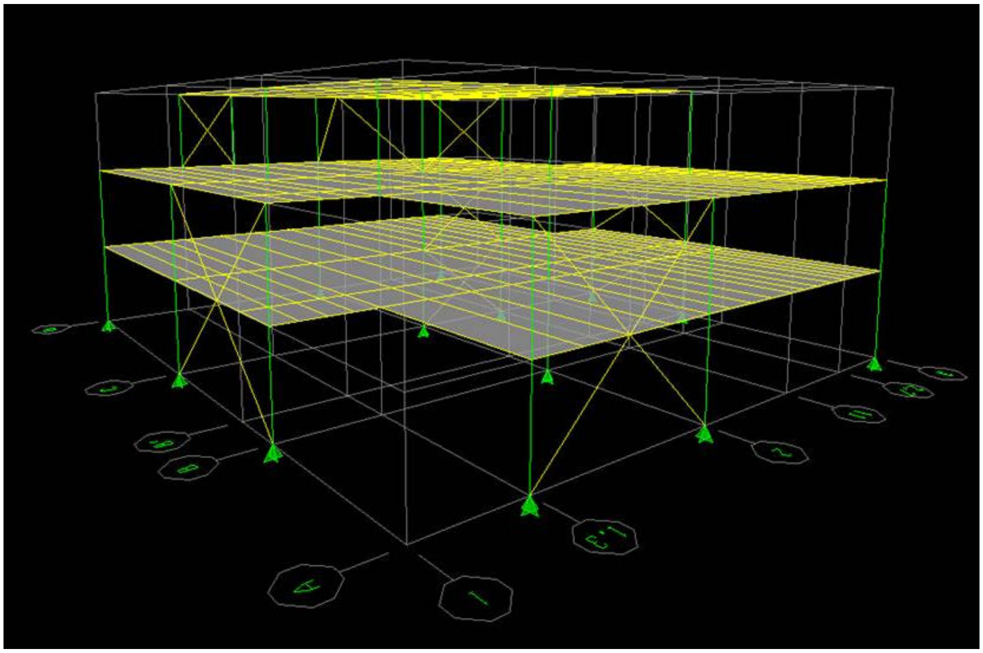

Figure 2: Typical Student Analytical Model

With these assumptions, the students were given the structural plans for the building, access to two modern commercial structural analysis programs (RISA and ETABS), and access to Matlab to aid in their “hand” calculations. They were told to predict the first (highest) natural period of lateral vibration using a 9-degree-of-freedom (3 per floor) “hand” calculation model and then again using the structural analysis software. Prior to this exercise, the students had performed “hand” calculations on a simpler 2-story 3D laboratory model, had taken a quarter-long matrix structural analysis course, and had been introduced to the commercial structural analysis software. The students were instructed not to spend more than 10-12 hours on this assignment. To ensure that the students took their work seriously, 4% of their final grade was assigned to the exercise.

Laboratory Results

The students were given one week to come up with their hand and computer-based predictions of the buildings first natural period of vibration. On the due date, the students were asked to write their two predictions on the chalkboard and discuss their results. While those with the most extreme results knew they had made errors, interestingly enough the majority of the students thought they had presented reasonable predictions.

Of the 22 students who performed the exercise, twenty were able to hand in final results for computer-based analysis – two students were not able to create models that resulted in predictions for the fundamental period of the building due to errors in modeling. Eighteen students completed the hand calculations – four students ended up with imaginary answers for their eigen-solution. However, even disregarding those without a solution, the students performed poorly (see figure 3). The results the students presented for the prediction of the fundamental period of the building using computer software ranged from a low of 0.04s to a high of 14.4s. For their hand calculations, the period ranged from 0.17s to 6.6s. Worse still, the results were not centered on 0.32s, the period determined from subsequent ambient vibration testing of the building. The median value for the computer calculations was 0.56s with a standard deviation of 0.45s. For the hand calculations, the median value was 0.59s with a standard deviation of 0.94s. In light of the fact that these students will be entering the workforce within one year, this is clearly an unacceptable result.

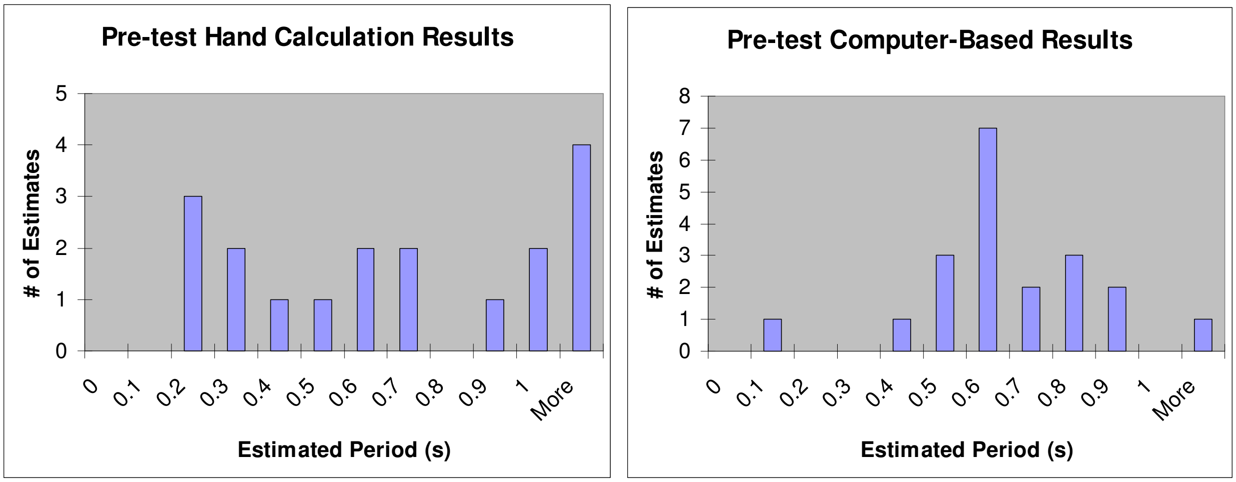

Figure 3: Computer and Hand Calculation Results Prior to the Ambient Vibration Test

The student hand-calculations contained a typical array of errors in stiffness matrix calculations including: geometric errors; resultant force and moment calculation errors; incorrect placement of a term within the stiffness matrix; and member property errors. On the mass matrix side of the calculations, the vast majority of the errors arose in the rotational inertia term – usually resulting from an error in their statics calculations. The random nature of the errors in the stiffness and mass matrices no doubt lead to the large scatter in the student's predictions.

When faced with such a wide variation in their predictions, the students were asked to predict where inaccuracies in their computer-based models may have arisen. For the most part the students pointed to modeling decision errors such as: neglecting the stiffness of non-structural components; additional flexibility in the steel connections; participation of the bridge or stairwell; and neglecting the flexibility of the diaphragms. While their modeling decisions were generally good, it was the implementation of these decisions within the software that caused the most influential problems. In other words, while they knew what they wanted in the model, they simply failed to achieve it. More importantly, they failed to check whether they had achieved it. The highlights of their implementation errors include:

- A portion of the lateral resisting structure not attached to one or more diaphragms
- Unrestrained vertical vibration of the diaphragms due to missing gravity columns
- Random unnecessary appendages vibrating at a low frequency/high period
- Mistaken units (kips instead of pounds, feet instead of inches)
- Incorrect structural sizes
- Incorrect boundary conditions
- Failure to include non-structural mass

Following the student discussion of the results, the class walked over to the building to perform an ambient vibration test to determine the actual period of vibration (see figure 4). Ambient vibrations exist at very low levels (<100μg) in all structures and are typically caused by wind and occupancy loads. This test was performed using an extremely sensitive piezo-electric accelerometer (resolution of 4μg) hooked it up to a filtered power supply/amplifier and a standard data acquisition system. The results were digitally filtered to remove the erroneous low frequency (< 1Hz) signals and the structurally irrelevant higher frequency (> 20 Hz) data. The tests were repeated several times by the students to ensure elimination of non-structural transient frequencies. A typical Fast-Fourier-Transform of the measured signal is shown in figure 4. As can be seen, the lowest dominant frequency obtained by the students was 3.12 Hz. This corresponds to a period of vibration of 0.32s (this result was independently confirmed by a more complex Forced Vibration Test performed by the faculty in advance of the student run ambient vibration test). The fundamental period of vibration will vary as the amplitude of the forced vibration increases[2,5], however, no significant variation was measured under forced vibrations exceeding 40 times the ambient vibrations.

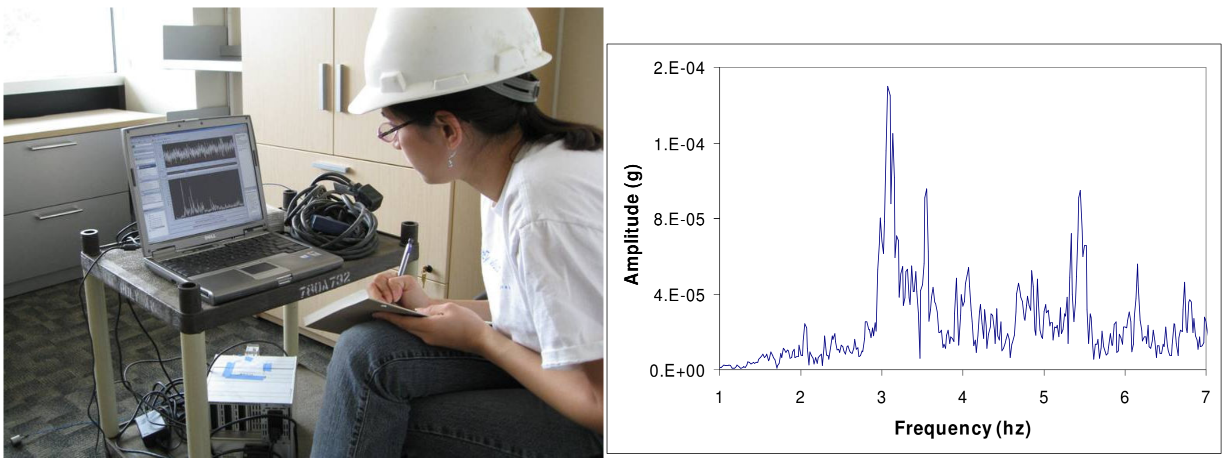

Figure 4: Student-run Ambient Vibration Test

Upon performing the ambient vibration test and confirming the period of vibration, the students were somewhat stunned and embarrassed. While they had no problems with the fact that their hand calculation were in error, they were shocked that "the computer gave them incorrect results". In fact, 13 students volunteered to redo the computer-based exercise in light of the test results. For this exercise they were provided with no additional instruction in the use of the software. However, of course they knew the correct answer from the ambient vibration test. It could be argued that knowing the answer ahead of time invalidates the results. However, the authors would like to point out that any experienced engineer would have a rough idea of the period of the modeled structure before creating a model. A long held rule-of-thumb of 0.1s per floor (thus 0.3s for the three-story building) is so prevalent in the industry that it is codified as equation 12.8-8 of ASCE/SEI 7-05[1]. In other words, a student redoing the exercise knowing the actual result of 0.32s is similar to a practicing engineer expecting a result of around 0.3s.

A histogram of the student computer-based revised predictions of the natural period of vibration is given in figure 5. As can be seen, the results represent a dramatic improvement. The median result was 0.4s, with a standard deviation of only 0.08s. Since the students did not model the non-structural system or the gravity-only framing, the predicted period is expected to be slightly higher than the measured period. In fact the project structural engineers predicted a period of 0.5s. When queried, the students attributed the improvement in their results to two basic reasons. First, when the computer results were far in excess of the anticipated period, the students spent time reviewing their use of units and more importantly analyzing the accompanying mode shape to see which part of the structure was too flexible or not properly attached. Secondly, for moderate discrepancies the students generally reviewed their input data more finely to search out incorrect member selection and mass assignment.

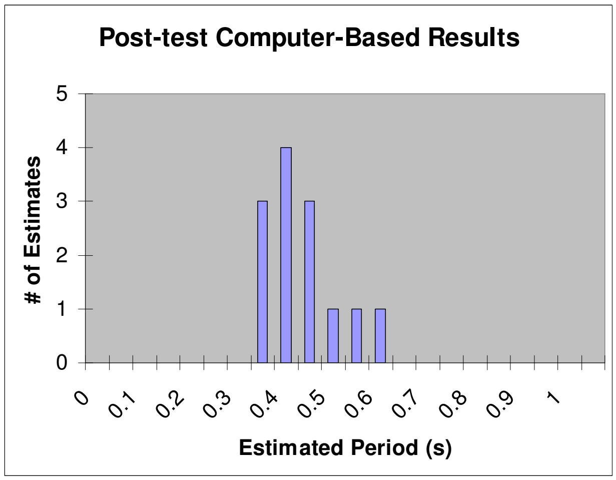

Figure 5: Revised Computer-Based Results

This exercise was successful in both building a healthy skepticism in students about computer analysis results and completing the prediction/experimentation/refinement loop. It left students responding with the following question: "How do we know if our computer model is any good?" After this exercise students were eager to investigate ways to improve their modeling skills.

Conclusions

The laboratory experience described above aimed at improving students' ability to use computers to accurately model the dynamic response of buildings. One of the roots of the problem is the lack of skepticism by students with computer analysis results, a dilemma challenging many engineering disciplines. Unfortunately, significant progress has not been made in improving education in the area of modeling structural system behavior.

After experiencing the laboratory which included modeling the building dynamic response (prediction), measuring the building dynamic response (experimentation), comparing the results with classmates, the building designers and the measured response, and improving the initial modeling of the building (refinement), the students grew skeptical of their computer results, one of the main goals of the laboratory. In addition, after this exercise students were eager to investigate ways to improve their modeling skills. Future research in this topic will be aimed at developing additional laboratories to broaden the exposure students have to modeling structures and to further develop a students' 'feel' for the behavior of structures with the goal of disseminating the laboratory exercises to interested engineering programs across the country and throughout the world.

Bibliography

1. American Society of Civil Engineers (ASCE), 2006. *Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-05)*, Reston, VA.
2. Celebi, M., Phan, L.T., Marshall, R. D., 1993. *Dynamic Characteristics of Five Buildings During Strong- and Low-Amplitude Motions*, International Journal of the Structural Design of Tall Buildings.
3. Kennedy, T.C., 2006. *The Value Added Approach to Engineering*, The Bridge - National Academy of Engineering, Vol. 36, No. 2.
4. Vest, C. M., 2006. *Educating Engineers for 2020 and Beyond*, The Bridge - National Academy of Engineering, Vol. 36, No. 2.
5. Yu, E. Skolnik, D., Whang, D., Wallace, J., 2008. *Forced Vibration Testing of a Four-Story Reinforced Concrete Building Utilizing the nees@UCLA Mobile Field Laboratory*, Earthquake Spectra, Vol. 24, No. 4.