Classroom-Based Forced-Vibration Testing

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SUMMARY:
A unique series of laboratory modules, in part funded by NSF NEESR, were recently developed to improve student computational modeling of buildings. Undergraduate students were challenged with the task of predicting the natural periods of vibration and mode shapes of several buildings on campus using computer software and then comparing their results to those from ambient and forced vibration tests performed by the students themselves. Since an actual structure is used, the validity and practicality of the experiment is obvious. The range of results the students presented for the prediction of the fundamental period of the building using computer software varied widely. Future research in this topic will be aimed at developing additional modules to broaden the exposure students have to modeling structures with the goal of disseminating the laboratory exercises to interested engineering programs across the country and throughout the world.

Keywords: forced-vibration, modelling, dynamics, education

1. INTRODUCTION

Upon graduation, structural engineering students are often not able to create a sufficiently accurate computational model of a building structure. Unfortunately, this is the very task that many young engineers are asked to perform. Despite the call by both engineers and academia for improved education in the area of structural-behavior modeling, significant progress has not occurred. Why has the progress been so slow? Accurately modeling the behavior of structures with computer software requires a ‘feel’ for structural behavior. In other words, you need to understand the phenomena you are modeling in order to develop the model. Developing this knowledge is a life-long endeavor; however, the foundation needs to be laid in the undergraduate education. While computational modeling provides students the opportunity to apply concepts from design and analysis courses to predict the building behavior, the authors have found that providing students with the experience of testing a real-world building enhances student learning and retention dramatically (McDaniel and Archer 2009, 2010).

2.0 EXPERIMENTAL SETUP

Ultra-low Forced Vibration Testing (UL-FVT) has been developed to give students the opportunity to experiment with actual buildings. The UL-FVT procedure consists of four phases: 1) an initial broad-range ambient vibration test (AVT) to determine the likely range of structural frequencies; 2) an FVT over a more narrow range of frequencies to accurately determine the natural modal frequencies; 3) a very narrow range FVT to determine modal damping ratios; and 4) a fixed frequency FVT to determine the mode shape.

The heart of the UL-FVT test equipment is a small portable linear shaker with a total weight of about 100 lbs (Fig. 2.1). The shaker is capable of putting out a relatively constant sinusoidal force of 30 lbs over a frequency range of 2-20 Hz. The sensors used are piezoelectric flexural accelerometers with frequency ranges of less than 1 Hz to greater than 200 Hz and advertised broadband resolutions of 1-

3 μg rms. Three sensors are used, two perpendicular to each other and one parallel but separated from the first to capture floor rotations about a vertical axis.

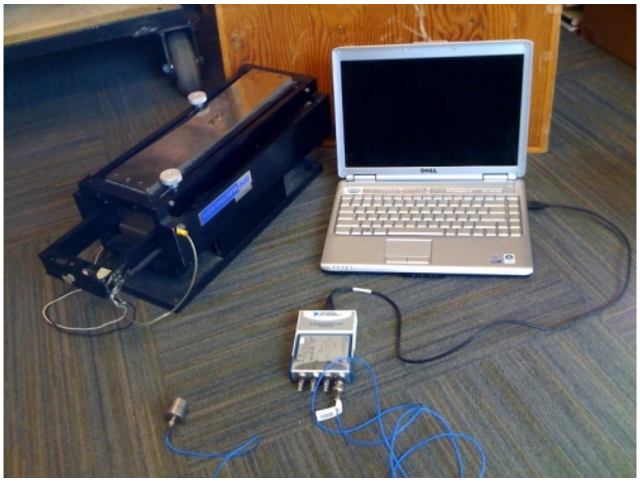


Figure 2.1. Test equipment

The constant battle in the UL-FVT is with the always present ambient noise. The shaker's 30 lb harmonic force produces structural accelerations that are only significantly above the ambient noise at resonance. Thus FVT methods involving white noise are not applicable. The white noise put out by such a small shaker is not sufficient to drown out the variable ambient noise. Thus once the structure's natural frequencies are identified by the AVT and FVT sweep test, the shaker is set at the natural frequency and placed to maximize its effect on a single mode and minimize its effect on adjacent modes. The placement is an educated trial and error process. The resulting floor accelerations are then measured at selected locations throughout the building to estimate the mode shape. Even with careful shaker placement, it is not possible to excite a single mode. The shaker will undoubtedly not be orthogonal to some modes. Given modal coupling through damping, these mode shapes will be present in the measured values. Thus they are numerically swept out using a Modified Gramm-Schmidt algorithm (Golub 1989).

In order to more precisely compare two mode shapes, a modal assurance criterion (MAC) (Allemang 2003) is employed. The MAC number represents a decimal percent of the correlation between two modes (1.0 would represent perfect correlation). Since the mode shapes contain both translational and rotational acceleration with different units and orders of magnitude, the typical MAC number equation is modified (McDaniel and Archer 2010) to include the approximated mass matrix as a weighting factor. The mass-weighted MAC number for shapes ϕ_i and ϕ_j is given as:

$$\mathrm{MAC}_{ij} = \frac{\left(\phi_i^t M \phi_j\right)^2}{\left(\phi_i^t M \phi_i\right)\left(\phi_j^t M \phi_j\right)} \tag{2.1}$$

3.0 CASE 1: ROTATIONAL INERTIA MODELLING

Three laboratory modules using the UL-FVT described above to improve student learning of structural dynamics and computational modeling are presented below. One typical modeling error made by young engineers is that of rotational inertia. This often occurs when a floor diaphragm constraint is incorrectly applied. As a result the mass of the diaphragm is lumped to the corners of the rigid diaphragm. Thus the rotational inertia is artificially increased. The building selected to illustrate this phenomena is the newly constructed Construction Management building on the Cal Poly San Luis

Obispo campus (Fig. 3.1). 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.

Figure 3.1. Construction Management building

In this structure, both the brace layout and mass distribution is unsymmetric in plan. In previous work (Archer and McDaniel 2011) the first three mode shapes and natural frequencies were found by the authors and are displayed in Fig. 3.2. The first mode is primarily in the North-South direction and the second mode is primarily East-West. However both mode shapes contain a significant rotational component. The third mode is a mixture of North-South and East-West translation as well as rotation.

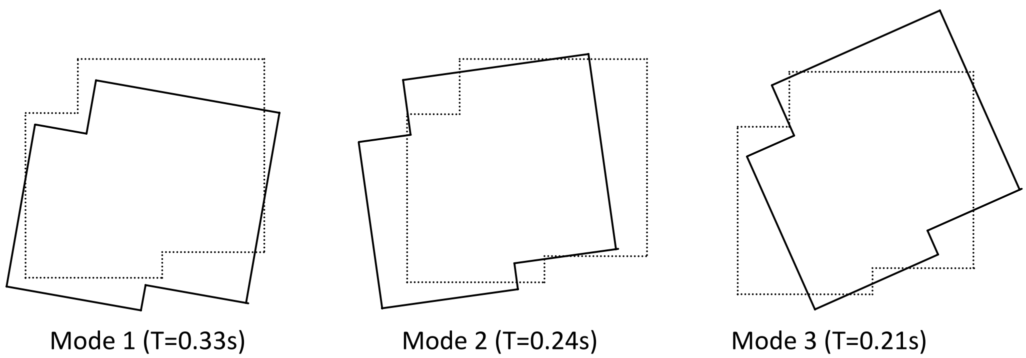
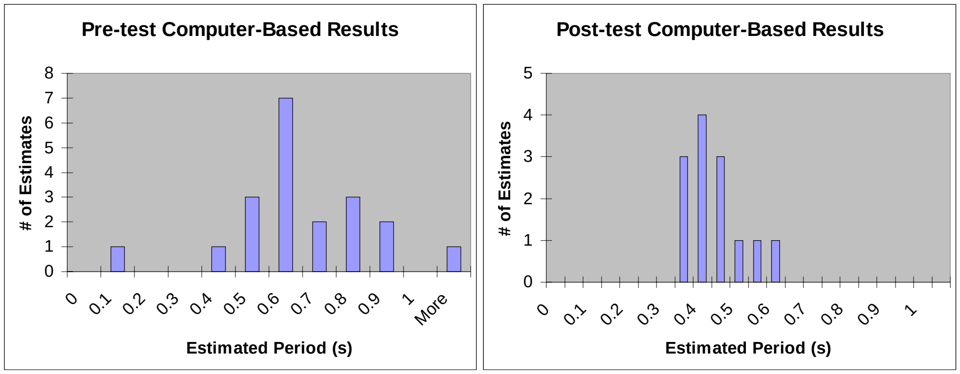


Figure 3.2. Experimentally determined mode shapes

The students were assigned the task of generating computer-based predictions of the building's first natural period of vibration. On the due date, the students were asked to write their 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 (Fig. 3.3a). The median value for the student computer calculations was 0.56s with a standard deviation of 0.45s. Unfortunately the first natural period (verified by both experiment and an appropriate faculty created computer-based model) is 0.33s. In light of the fact that these students will be entering the workforce within one year, this is clearly an unacceptable result.

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.



(a) (b)

Figure 3.3. Results (a) before and (b) after the ambient vibration test

Figure 3.4. Student ambient vibration and forced vibration testing

Upon performing the ambient vibration test and confirming the period of vibration (Fig. 3.4), 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, an 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. In other words, a student redoing the exercise knowing the actual result of 0.33s 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 Fig. 3.3b. As can be seen, the results represent a dramatic improvement. The median result was 0.4s, with a standard deviation of only 0.08s. This is a clear improvement over the results prior to the physical test. However, it is clear that the results are not centered on the correct answer of 0.33s. A closer inspection of the predicted mode shapes by the students revealed the error. The student mode shapes primarily consisted of a rotation about the center of the building with very little horizontal translations. In other words, their first mode prediction was similar to the actual third mode shape. In modeling the rigid diaphragm, the students had chosen options that lumped the mass of the diaphragm to the corners. Thus they over-predicted their rotational inertia. This error ended up producing a rotational first mode with a very high period -- clearly an inappropriate model for seismic analysis. This exercise was successful in building a healthy skepticism in students about computer analysis results.

4.0 CASE 2: Diaphragm Flexibility

Another typical modeling error made by young engineers is the assumption of a rigid diaphragm for all concrete floors and roofs. In order to investigate diaphragm rigidity, students experimented with Unit 5 of the Engineering West Building 21 (EWB Unit 5) located on the campus of California Polytechnic State University, San Luis Obispo (Fig. 4.1). The students created a computational model using commercial structural analysis software (CSI 2008) in order to predict the dynamic response of the building including natural frequencies, mode shapes, and accelerations when subject to a dynamic load. Based on the building aspect ratio of 2.67, ASCE 7-05 (ASCE 7-05 2006) allows for the use of a rigid diaphragm to model the building. Therefore, the students originally modeled the building assuming a rigid diaphragm. The student average fundamental frequency prediction was 9.2 Hz. The fundamental mode was primarily translation in the North-South direction without any diaphragm flexibility due to the rigid diaphragm constraints.

(a) (b) (c)

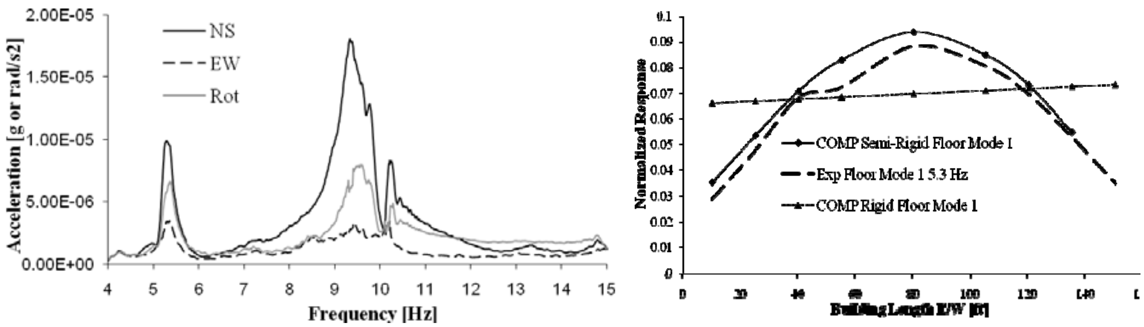
Figure 4.1. EWB Unit 5 a) plan b) elevation c) student computational model

The next phase of the student exercise was to physically shake the campus building and record the resulting motions. The students experimentally determined the fundamental frequency to be 5.3 Hz. Next the students experimentally determined the shape (mode shape) the building takes on as it vibrates at its first natural frequency. To accomplish this, the students set the shaker running at 5.3 Hz and then placed the accelerometer at various points down the second story corridor (Fig. 4.2). The student results for the experimentally derived mode shape are shown in Fig. 4.3 along with their results for their rigid and semi-rigid diaphragm models. From Fig. 4.3, the students rightfully concluded their rigid diaphragm model failed to capture the building response while their semi-rigid diaphragm model reasonably captured the behavior of the building.

The students were asked to compare their analytical predictions for the natural frequency of the building and explain the differences in comparison to the experimental results. Their rigid diaphragm model grossly overestimated the stiffness of the floor and roof and hence produced a much higher frequency estimate of 9.2 Hz while failing to capture the diaphragm flexibility. Next the students then updated their computational models to include diaphragm flexibility. The resulting fundamental frequency for the semi-rigid diaphragm computational model was 5.4 Hz. This prediction compared well with the experimental result of 5.3 Hz. The frequency predictions and experimental results are listed in Table 4.1.

(a) (b)

Figure 4.2. Students shaking the campus building



(a) Fast Fourier Transform (b) Mode 1 diaphragm deflected shape

Figure 4.3. Student experimental shaking results for EWB #5

Table 4.1. Student frequency predictions and experimental results for EWB #5

Student rigid diaphragm	Student Flexible diaphragm	Experimental
$f_{average}$=9.2 Hz	$f_{average}$=5.4 Hz	f=5.3Hz

In order to determine when a flexible diaphragm model is appropriate the students calculated the stiffness of the lateral force resisting system and the lateral stiffness of the diaphgram in EWB #5. The ratio of the diaphragm stiffness to the lateral force resisting system stiffness was found to be 0.15, providing insight into the flexible response of the diaphragm. To give students a contrast, they were provided with the dynamic response of a steel braced frame structure on campus with a similar aspect ratio of 2.63 (Roskelley 2010). Consequently the building did not display a flexible diaphragm response. Calculation of the ratio of the diaphragm stiffness to the lateral force resisting system stiffness yielded a value of 3.56, over 20 times larger than EWB #5.

Through this process of predicting building behavior computationally and experimentally determining the building response, the students learned a valuable lesson with regards to the modeling of floor and roof diaphragms. The influence of the ratio of the diaphragm stiffness to the lateral force resisting system stiffness was also effectively displayed.

5.0 CASE 3: Complex Shear Walls and Large Diaphragm Openings

By far the most complex of three campus buildings experimented with by students; the Robert E. Kennedy Library (Fig. 5.1) provided an ideal opportunity for students to model an irregular building and experiment with the dynamic response. The students were charged with predicting the fundamental frequency of the building through a series of increasingly detailed models. The structure is a five-story reinforced concrete shear wall building constructed in 1977. Of particular challenge to the students was the complex wall layout shown in Fig. 5.2; C, T, L and box shaped walls added to the difficulty of accurately predicting the building dynamic response.

Figure 5.1. Robert E. Kennedy Library; plan view of the Kennedy Library

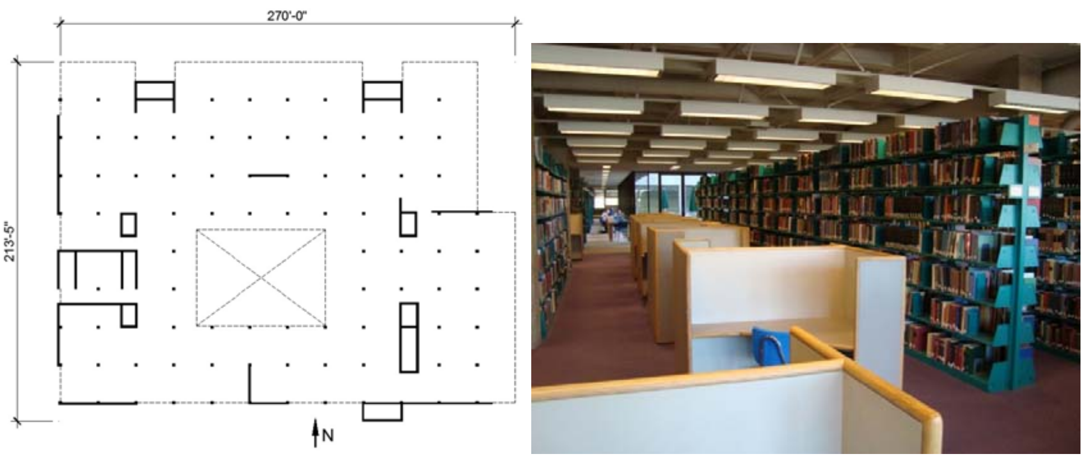


Figure 5.2. 2nd floor plan of building; typical arrangement of furniture and books

Modeling of the Kennedy Library progressed from a simple hand calculation analysis to a detailed computational model (Fig. 5.3). Students first modeled the building with hand calculations ignoring shear flexibility. As is common in undergraduate engineering courses, shear stiffness is often ignored to simplify the analysis. However, students quickly realized that the model was far too stiff, with an average first mode frequency prediction around 20 Hz, much larger than the experimental result of 3.3 Hz. By including shear stiffness the average first mode frequency prediction decreased to 6.4 Hz.

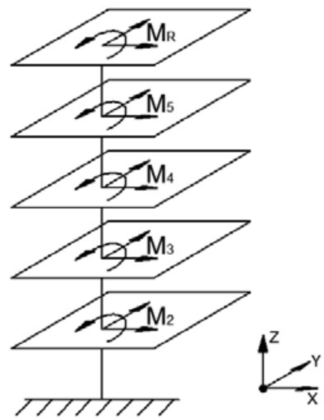
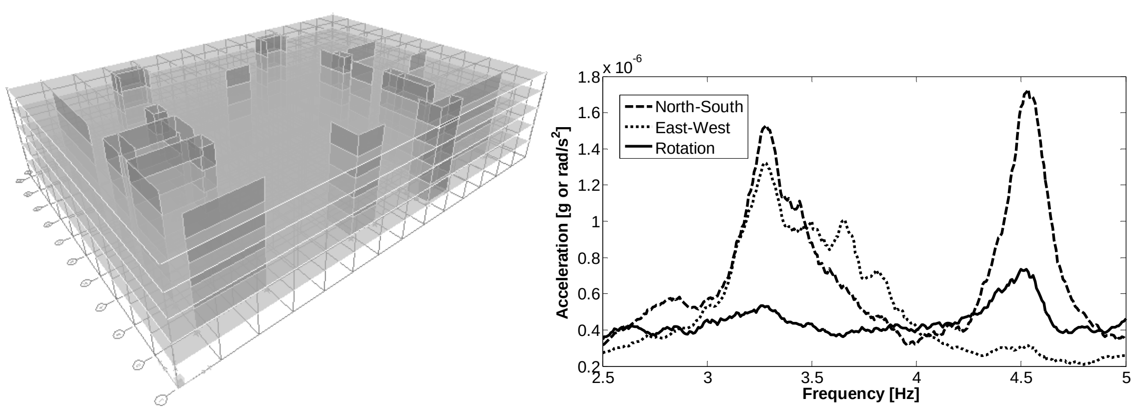


Figure 5.3. Hand calculation model of the Kennedy Library, 3 degrees-of-freedom/floor

The next step was for students to model the building computationally (Fig. 5.4) and calibrate it to the hand calculations. Once the computational model was calibrated the double bending constraint at the diaphragm level was removed, another simplification often used in undergraduate engineering courses. By allowing more than three degrees-of-freedom per floor, the average first mode frequency decreased to 2.4 Hz.



(a) (b)

Figure 5.4. (a) Student computational model (CSI 2005) (b) Kennedy Library FFT results

The students were then given the opportunity to shake the library and determine the experimental first mode frequency of 3.3 Hz (Fig. 5.4b). This experimental frequency showed that student models were too low in frequency. The average of the student fundamental frequency computational predictions and experimental results are summarized in Table 5.1. When students were asked to postulate why their computational models predicted a low frequency, most students pointed to influence of the atrium and the library book mass as the most likely sources of error. However, a recent master's thesis (Rendon 2012), which details the influence of key variables on the first mode frequency, showed that the atrium had little influence on the first mode frequency. Since the mass the students calculated included a rough estimate of the live load and library book mass it is a likely contributor to the large gap in the results. The next issue to consider was properly modeling the reinforced concrete shear walls. Students chose to model the shear walls with 4 node elements, even though they had not derived the stiffness matrix for these elements in previous courses, rather than choosing column elements which the students had studied in detail in a previous structural analysis course. Issues of mesh density and inaccurate torsional stiffness of the 4 node elements used to model C, T, L and box shaped walls (Wilson 2002) were not considered by the students. This combination resulted in models that the students were not prepared to debug.

Table 5.1 Average student fundamental frequency computational predictions and experimental results

Model Assumptions	Mode 1 natural frequency
- Walls modeled as disconnected rectangular elements in double bending Neglect shear and torsional stiffness	20.1 Hz
- Include wall shear stiffness	6.4 Hz
- Remove double bending constraint	2.4 Hz
- Experimental data	3.3 Hz

Although further improvement of the computational models was beyond the scope of the student exercise, it served as an excellent example of the 'blind use' of structural analysis software. The students were also reminded that they should "not use an equation they cannot derive" (Wilson 2002); specifically related to their lack of understanding of the limitation of 4 node elements in common computational analysis programs. Upon reflection, students gained valuable insight into modeling complex buildings including modeling irregular shear walls as well as considering the effects of large diaphragm openings.

6.0 CONCLUSIONS

While computational modeling provides students the opportunity to apply concepts from engineering design and analysis courses to predict building behavior, the authors have found that providing students with the experience of testing a real-world building enhances student learning and retention dramatically. Ultra-low Forced Vibration Testing (UL-FVT) was developed to provide students the experience of testing of actual buildings with the goal of improving understanding of structural dynamics concepts and computational modeling. Three laboratory exercises were presented in this paper to illustrate the benefits of bringing UL-FVT into the classroom. In each case students experimented with buildings using UL-FVT to gain a better understanding of a particular phenomena, specifically the effect of rotational inertia, the effect of diaphragm flexibility, and the effect of complex shear walls and large diaphragm openings. In each case the students compared their prediction of the modal parameters of the building through hand calculations, ambient vibrations tests, forced vibration tests, a computational model in current commercial software and the prediction of other classmates. In all three exercises, when the students compared their predictions to the actual building response, the difference was significant, creating an eagerness to investigate ways to improve their modeling skills. These exercises were successful in improving student comprehension of key structural dynamics concepts as well as building a healthy scepticism in students about computer analysis results.

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REFERENCES

ACI committee 318. (2008). Building Code Requirements for Structural Concrete and Commentary, ACI 318-08. Farmington Hills, Michigan: American Concrete Institute.
Allemang. (2003). The Modal Assurance Criterion – Twenty Years of Use and Abuse, *Sound and Vibration*.

Archer, G. C., McDaniel, C.C. (2011). Determination of Building Modal Parameters Using Low-Level Excitation. *Architectural Engineering Institute (AEI) Annual Conference,* 2011.

CSI Analysis Reference Manual. (2005). Berkeley, California: Computers & Structures Inc.

Golub G.H., Van Loan C.F. (1989). Matrix Computations: Second Edition. Baltimore: Johns Hopkins University Press.

McDaniel, C.C., Archer, G. (2009). Developing a 'Feel' for Structural Behavior. *American Society for Engineering Education (ASEE) Annual Conference*.

McDaniel, C.C., G. C. Archer. (2010). Full-scale, Real-time Building Dynamics Laboratory. *9th U.S. National and 10th Canadian Conference on Earthquake Engineering.* Earthquake Engineering Research Institute.

McDaniel, C.C., G.C. Archer. (2010). Improving Student Understanding of Structural Dynamics Using Full-scale, Real-time Excitation of Buildings. *American Society for Engineering Education (ASEE) Annual Conference*.

Rendon, A. (2011). Determination Of The Modal Parameters Of A Five Story Reinforced Concrete Structure Using Ultra-Low Level Excitation And Computational Analysis. *Master's Thesis*, Architectural Engineering Department, California Polytechnic State University, San Luis Obispo.

Roskelley, B. (2010). An Investigation of the Influence of Diaphragm Flexibility on Building Design Through a Comparison of Forced Vibration Testing and Computational Analysis. *Master's Thesis*, Architectural Engineering Department, California Polytechnic State University, San Luis Obispo.

The Structural Engineer Institute of the American Society of Civil Engineers. (2006). Minimum Design Loads for Buildings and Other Structures, ASCE 7-05. American Society of Civil Engineers.

Wilson, E.L. (2002). Three-Dimensional Static and Dynamic Analysis of Structures. Berkeley, California: Computers and Structures Inc.