AC 2010-338: IMPROVING STUDENT UNDERSTANDING OF STRUCTURAL DYNAMICS USING FULL-SCALE, REAL-TIME EXCITATION OF BUILDINGS

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Improving Student Understanding of Structural Dynamics Using Full-Scale, Real-time Excitation of Buildings

Abstract

Current engineering educational practices often fail to prepare students to use computers effectively. In the field of structural engineering, fresh graduates frequently produce computational models of a building structure that bear little resemblance to reality. Unfortunately, the construction of a computational model is typically one of the first tasks a young engineer is asked to perform. In order to address this issue, the authors are constructing a series of experimental and analytical laboratory exercises which challenge the student's confidence in computer results. In the current work, forced vibration tests of the building are performed to obtain both the natural frequencies and the resulting mode shapes. In this paper, the procedure to experimentally determine the mode shapes is described. The student predictions of the building response before and after experiencing the ambient and forced vibration laboratories are then examined. One might think that experimentally determining the mode shapes is a simple task, the reality is quite different. The basic concept is to mildly (below human perception) shake the structure and record the resulting motions in a variety of locations. However the positioning of the shaking and data collection equipment and interpretation of the results must be carefully considered. The results of this experiment were found to be very enlightening for the students; experimental and analytical observation of the mode shapes gave students a much deeper understanding of the structural behavior and the underlying structural dynamics theory.

Introduction

In spite of our best efforts, current engineering educational practices fail to prepare students to use computers effectively. In the field of structural engineering, fresh graduates often produce computational models of a building structure that bear little resemblance to reality. Unfortunately, the construction of a computational model is typically one of the first tasks a young engineer is asked to perform. An understanding of the phenomenon being modeled as well as the limitations of the software is necessary to accurately model the behavior of a building. In order to address this issue, the authors are constructing a series of experimental and analytical laboratory exercises which challenge the student's confidence in computer results.

Last year, the authors presented a paper[6] comparing student computational modeling before and after a simple ambient vibration test[7] to determine the building's natural frequencies of vibration. Senior undergraduate students in their terminal analysis course were challenged with the task of predicting the natural frequencies and mode shapes of a building on campus using computer software. Their results were then compared to those from an ambient vibration test. The students revised their computational models and produced significantly improved estimates of the natural frequencies. However, review of the student's mode shapes indicated a very weak correlation with the mode shapes predicted by the faculty.

In the current work, the experimental procedure was greatly expanded to include forced vibration tests[8] of the building to obtain both the natural frequencies but also the resulting mode shapes. In this paper, the procedure to experimentally determine the mode shapes is described as well as the student predictions of the building response before and after experiencing the ambient and forced vibration laboratories. One might think that experimentally determining the mode shapes is a simple task, the reality is quite different. The basic concept is to mildly (below human perception) shake the structure and record the resulting motions in a variety of locations. However the positioning of the shaking and data collection equipment and interpretation of the results must be carefully considered. The results of this experiment were found to be very enlightening for the students; experimental and analytical observation of the mode shapes gave students a much deeper understanding of the structural behavior and the underlying structural dynamics theory.

Testing Equipment

In order to create a laboratory for students to conduct ambient and forced vibration testing on full-scale buildings, the loading and data acquisition equipment needed to be selected and validated. The equipment described below is by no means an ideal setup. Future research will focus on developing a system of equipment that is readily transferable to other engineering programs. The test equipment consists of a shaking device to excite the structure and accelerometers and a data acquisition system to obtain and process the building motions. The heart of the test equipment is a portable long-stroke linear shaker with a total weight of about 100 lbs (see Fig. 1). The shaker is capable of putting out a relatively constant sinusoidal force of only 30 lbs over a frequency range of 2-20 Hz. Due to the small forces involved, the shaker need not be mechanically attached to the structure – friction at its base is sufficient. This shaker is appropriately sized for scale models of buildings and bridges. Nonetheless, the authors have found that when appropriately placed in low-rise structures (<4 floors, <30,000 sq ft), the shaker can induce motions detectable throughout the building on all floors. Typical induced floor accelerations range from about 20-40 μg when the shaker is not driven at the natural frequency of the building, to 50-500 μg when the shaker is driven at one of the building's natural frequencies. These magnitudes can be compared to ambient accelerations, typically in the range of 5-10 μg at the natural frequencies of the building. HVAC units generate very narrow band accelerations detectable throughout the structure of up to 30 μg. All of these accelerations are far below the level of human perception and pose no risk to disrupting other activities in the building.

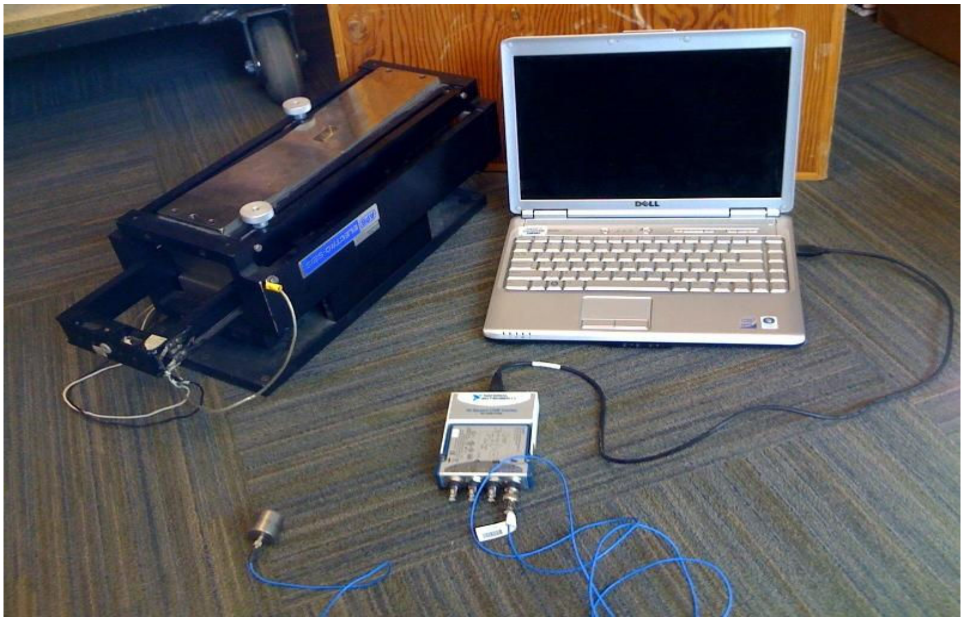

Figure 1: Test equipment (shaker, accelerometer, DAQ, computer).

To capture the building motions, 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 are used. The measurement range for the accelerometers is very large (up to 0.5g) relative to the measured signals of interest. Thus, in order for the analog signal from the accelerometers to be digitized without loss of accuracy, a standard 16 bit analog to digital converter was found to be insufficient. A 24-bit device specifically designed to handle 4 accelerometers without time-shifting is employed. Multiple accelerometers are required to capture the lateral x, y, and rotation (about a vertical axis) motions of a floor slab simultaneously.

The digitized data streams from the accelerometers were processed using standard lab software (MathWorks Inc. 2009)[5]. The software is set up to properly scale the signals from the various accelerometers and filter out low frequency (< 0.5 Hz) noise from the natural accelerometer drift and higher frequency (>10-20 Hz) non-structural noise originating from the building. To capture floor rotations the signals of two parallel accelerometers were processed to produce an additional data stream representing rotational accelerations in rad/s^2. Fast-Fourier Transforms (FFT) of the processed data is shown in real time alongside the time history view of the accelerations. The time history view is needed to discern the relative sign (pos. or neg.) of the translations and rotations. The peaks in the FFT plot are extracted and displayed on screen to aid in the data collection.

Ambient Vibration Test

The campus building selected to introduce the students to the theory and practice of structural vibrations was the newly constructed Construction Management faculty-office/classroom structure (see Fig. 2). 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 200 feet by 100 feet.

Figure 2: Construction Management Building

To provide a baseline, the students performed an ambient vibration test (AVT) by placing three accelerometers on the 3rd floor, 104' east and 7'south from the north-west corner of the building; one accelerometer in the North-South (NS) direction, one accelerometer in the East-West (EW) direction and a second accelerometer in the NS direction but spaced 16 feet from the first to provide floor rotations. An FFT plot of the results is shown in figure 3. The plots are the average of ten FFTs using 120 second windows. The lines have been smoothed by averaging the results 0.05 Hz on either side of the plotted value. The absolute magnitude of the accelerations is low since the ambient vibrations will appear within the sensitivity of the equipment for only portions of the measured window. The averaging of the results brings out the reoccurring nature of the structural vibrations and suppresses the randomly occurring transient noise.

As can be seen in figure 3, there are two major peaks in the NS data stream (3.6Hz and 4.6 Hz) and one major peak in the EW direction (3.9 Hz). In both the NS and EW direction there is a minor somewhat indistinct peak around 3.1Hz. The rotation data shows one noticeable peak at 4.6 Hz. From the ambient vibration data one could conclude that there are four natural modes of at 3.1, 3.6, 3.9, and 4.6Hz. As will be seen later, these conclusions will be shown to be only partially correct. Since the very nature of ambient vibrations entails an unknown forcing function (the background vibrational "noise"), the resulting FFT plot can be misleading. Nonetheless, it does provide an easily obtained estimate of the natural frequencies and valuable directions for further investigation.

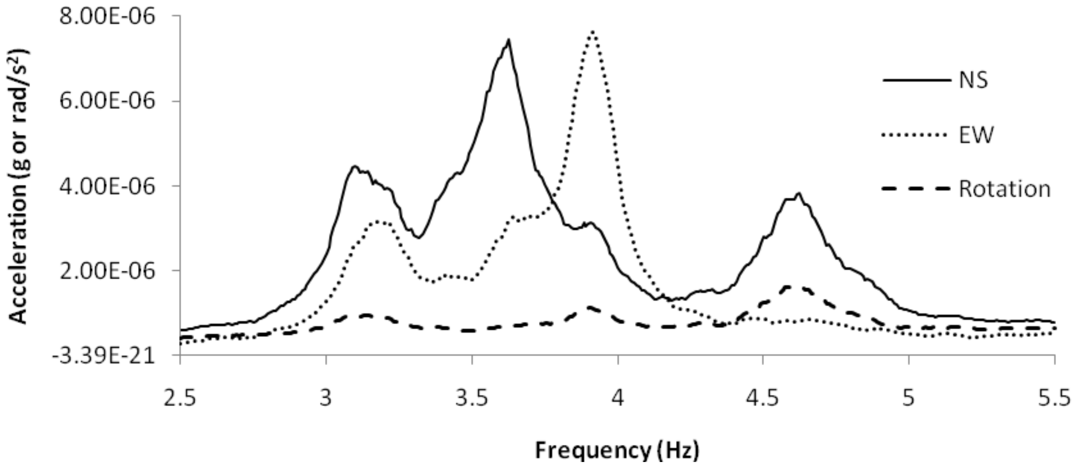

Figure 3: Ambient vibration response.

Forced Vibration Test

Based on the results of the AVT, the students placed the shaker in a SW to NE direction on the floor of the third floor (in the NW corner of the building). The shaker was set to continually sweep through 3 to10 Hz over a 120 second window with a constant amplitude of 30 lb. This window was set to match and synchronize with the FFT window to minimize the distortions caused when the shaker abruptly shifts from the maximum to the minimum applied frequency. The SW-NE orientation of the shaker was chosen to excite NS, EW, and rotationally biased modes. The rotational motion is particularly hard to excite with a single shaker – two shakers 180 degrees out of phase would be ideal.

An FFT plot of the forced vibration test (FVT) results is shown in figure 4. As it was for the AVT, the FVT plots are the average of ten FFTs using 120 second windows. The lines have been smoothed by averaging the results 0.05 Hz on either side of the plotted value. The magnitudes of the accelerations are higher than the AVT results, but since the shaker is acting at any given frequency in the range for only a brief instant, the averaging effect of the FFT window greatly reduces the plotted values. For example at 3.6 Hz the FFT result in the NS direction is 12 μg. If the shaker remained at 3.6 Hz for the entire 120s window the result is 163.5 μg.

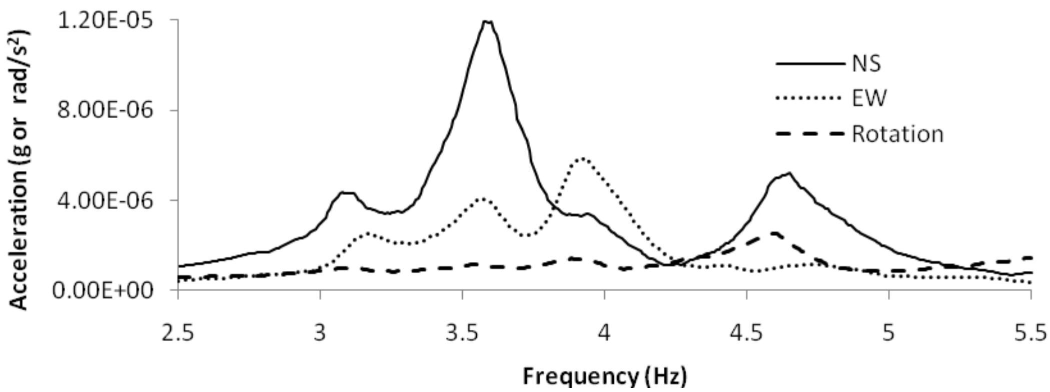

Figure 4: Forced vibration response.

Figure 4 shows three distinct peaks indicating the first three natural frequencies of vibration (3.61, 3.95, and 4.61 Hz). Most interestingly, the peak at 3.1Hz in the AVT plot is greatly diminished under forced vibration. It no longer appears to be a natural mode of vibration of the structure. In fact subsequent investigation revealed that it is the first natural mode of vibration of the adjacent building that is connected to the building at hand with an isolation joint. Thus, for the building under investigation, the first natural mode of vibration is at 3.61 Hz and the motion is primarily in the NS direction with some minor motion in the EW direction. The second mode occurs at 3.95 Hz and is strongly in the EW direction with some NS contribution. At the third mode (4.61 Hz) the motion appears to be primarily in the NS direction with some rotational component.

Looks however can be deceiving. Recall that all three FVT plots are the result of one shaker placement in the NW corner of the building in the SW-NE direction. This placement was chosen by the students to try to excite as many motions as possible. In fact for any given shaker frequency, potentially all of the natural modes of the building respond to some degree at the shaker's frequency. The amount of response from a given mode depends on how close the shaker's frequency is to the mode's natural frequency, the damping in the mode, and the degree of orthogonality between the load position and the mode shape. Thus, while the third mode appears to be mostly in the NS direction, in reality the combination of all modes excited by the shaker placement and frequency has produced a primarily NS response. The true mode shape remains to be isolated.

Damping

The damping ratio for each mode is found using the half-power band method[2]. For this, the students set the shaker to run for several minutes at each of a set of specific frequencies close to a given natural frequency of the structure. The peak response of a single accelerometer is then plotted against the driven frequency. Figure 5 represents such a plot for the first mode. The magnitude of the accelerations is much higher than those of the FVT sweep since the shaker is run at the given frequency for several minutes. Using the 4^{th} order polynomial line plotted through the data points, the frequencies that correspond to 0.707 times the peak response (at 3.61 Hz) are 3.52 Hz and 3.69 Hz. Thus the damping ratio for the second mode (ξ_1) is given by:

$$2\xi_1 = \frac{3.69 - 3.52}{3.61}$$

Thus the damping ratio for the second mode is 2.4%. The second and third mode damping ratios were similarly found to be 2.3% and 1.8% respectively.

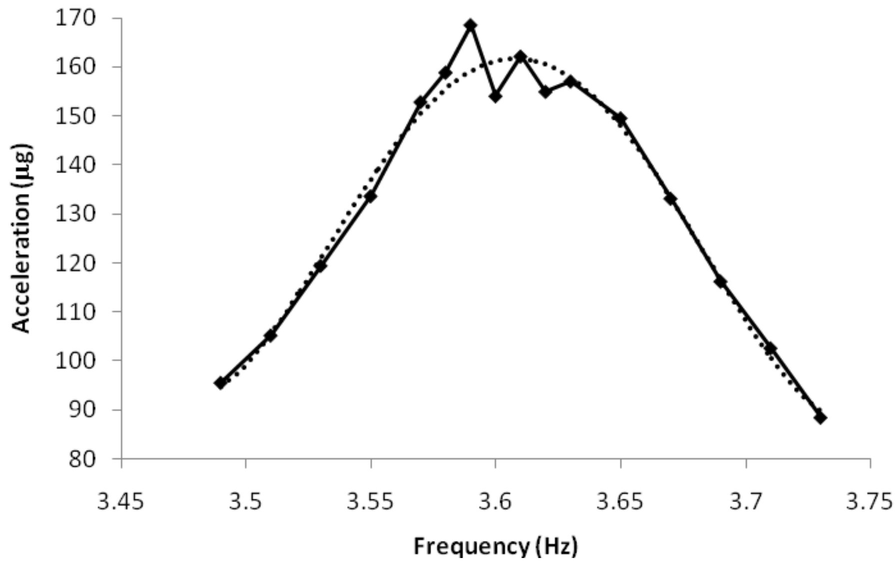

Figure 5: Mode 1 damping.

Mode Shapes

In order to determine the mode shapes, the shaker is run at the given natural frequency and the amplitude of the acceleration in each direction (x, y, and rotation) is determined from the FFTs at the given frequency. The positive and negative readings are interpreted from the time history display of the accelerometers. To aid in the determination of the sign, a tight band-pass filter is employed about the shaken frequency to remove the extraneous ambient noise.

The positioning of the shaker is of paramount importance for the determination of the mode shapes. The goal is to position the shaker in a way that maximizes the response of the mode of interest and minimizes the response of the adjacent modes. In addition, since the presence of slab rotations (about a vertical axis) will greatly affect the perceived NS and EW accelerations, the accelerometers were moved as close to the approximate center of mass of the floor slab. Unfortunately student access to the laboratories on the 2nd and 3rd floors that contained the predicted center-of-mass was not possible. In addition, access to the roof was not permitted. Thus locations in public hallways on the 2nd and 3rd floors, 104' east and 7'south from the north-west corner of the building was chosen to be as close as practical.

For modes 1 and 2, the FVT test indicated a strong NS component with a weaker EW component for mode1 and the reverse for mode 2. In both cases there was little to no rotational contribution. Thus, for mode 1 the shaker was run at 3.61 Hz and placed in the NS direction in line with, and to the north of, the center of mass (to help minimize rotations) and for mode 2 the shaker was run at 3.95 Hz and placed in the EW direction in line with, and to the east of, the center of mass. The measured accelerations are given in table 1. As predicted by the FVT, the motion is primarily

NS with some EW for mode 1 and the opposite for mode 2. Since the FVT results for mode 3 showed significant NS and rotational components, the shaker was placed in the NS direction as far from the center-of-mass as practical to excite both motions together. Nonetheless, the measured accelerations seem to indicate significant readings in all three directions.

Table 1 Acceleration readings

Acceleration Location	Mode 1 (3.61 Hz)	Mode 2 (3.95 Hz)	Mode 3 (4.61 Hz)
2nd floor EW (μg)	31.06	-62.09	-14.59
2nd floor NS (μg)	81.57	16.73	21.48
2nd floor Rotation (μ rad/s^2)	-21.59	14.69	32.69
3rd floor EW (μg)	71.41	-126.03	-30.93
3rd floor NS (μg)	163.5	30.29	48.43
3rd floor Rotation (μ rad/s^2)	-49.49	25.03	62.27

The raw accelerations shown in table 1 can be easily misconstrued. While the numbers all appear to be of similar magnitude, obviously the linear acceleration units are different from the rotational acceleration units. Furthermore, for each mode, the shaker was placed in a different orientation. Thus, even though the shaker sinusoidal load was kept at a 30 lb maximum, the modal load is different for each mode. A more equitable display of the modes is obtained by normalizing the mode shapes with respect to the mass matrix. A reasonable mass matrix for the structure can be constructed assuming a uniform mass per square foot for the floor slabs and half that for the roof slab (assigned to the 3rd floor mass). The resulting 6x6 mass matrix for the degrees of freedom in the order given in table 1 is given as:

$$M = \begin{bmatrix} 14117 & 0 & 421717 & 0 & 0 & 0 \\ 0 & 14117 & 64134 & 0 & 0 & 0 \\ 421717 & 64134 & 71384778 & 0 & 0 & 0 \\ 0 & 0 & 0 & 21176 & 0 & 632575 \\ 0 & 0 & 0 & 0 & 21176 & 96200 \\ 0 & 0 & 0 & 632575 & 96200 & 107077169 \end{bmatrix}$$

The resulting normalized acceleration vectors converted to feet and radians are:

$$\emptyset_1 = \begin{bmatrix} 1.062\,ft \\ 2.790\,ft \\ -0.02293\,rad \\ 2.442\,ft \\ 5.592\,ft \\ -0.05256\,rad \end{bmatrix} \emptyset_2 = \begin{bmatrix} -3.312\,ft \\ 0.8926\,ft \\ 0.02401\,rad \\ -6.724\,ft \\ 1.616\,ft \\ 0.04148\,rad \end{bmatrix} \emptyset_3 = \begin{bmatrix} -0.6617\,ft \\ 0.9743\,ft \\ 0.04604\,rad \\ -1.403\,ft \\ 2.197\,ft \\ 0.08771\,rad \end{bmatrix}$$

At this point it becomes evident that the results for mode 3 do indeed contain smaller translational motions than those for modes 1 and 2, but significantly larger rotations.

As mentioned previously all three measured “modes” are in fact not pure mode shapes. The intent of the placement of the shaker was to maximize the content of the desired mode and minimize the content of the other modes. However the other mode shapes will likely still be present. To resolve this, the Modified Gramm-Schmidt (MGS)[4] algorithm is used to sweep the unwanted modes out. For example, to sweep mode 1 (ϕ_1) out of mode 2 (ϕ_2) one would apply the following:

$$\phi_2' = \phi_2 - \frac{\phi_1^t M \phi_2}{\phi_1^t M \phi_1} \phi_1 \qquad (1)$$

Unfortunately, in order to apply this process, one needs a clean mode shape to start sweeping out of the other modes. Since a pure mode shape is not available, an approximate starting point must be assumed. In this case mode 1 was chosen. However mode 2 would have made an acceptable choice as well since it is predominately an EW motion. The authors are currently analyzing data from several buildings to better determine how the choice of this initial mode affects the resulting mode shapes. Sweeping mode 1 out of 2 and 3 and then sweeping the new mode 2 out of the new mode 3 results in the following final predicted mode shapes:

$$\emptyset_1 = \begin{bmatrix} 1.062\,ft \\ 2.790\,ft \\ -0.02293\,rad \\ 2.442\,ft \\ 5.592\,ft \\ -0.05256\,rad \end{bmatrix} \emptyset_2 = \begin{bmatrix} -3.2255\,ft \\ 1.166\,ft \\ 0.02191\,rad \\ -6.520\,ft \\ 2.163\,ft \\ 0.0366\,rad \end{bmatrix} \emptyset_3 = \begin{bmatrix} 0.5216\,ft \\ 0.9334\,ft \\ 0.03894\,rad \\ 1.017\,ft \\ 2.191\,ft \\ 0.0750\,rad \end{bmatrix}$$

These mode shapes are plotted in a plan view in figure 6.

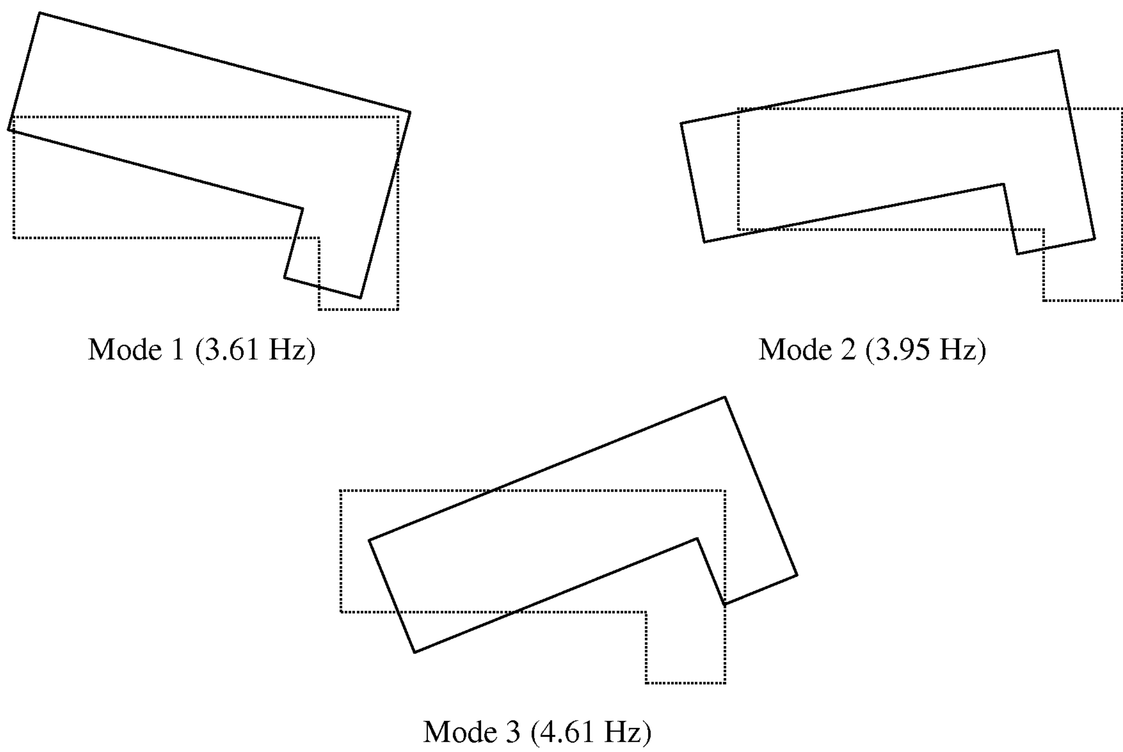

Figure 6. Experimentally determined mode shapes.

As can be seen in figure 6, mode 1 is primarily NS with some rotation, mode 2 is mostly in the EW direction with less rotation, and mode 3 is primarily rotational.

Comparison to Computational Results

The goal of the experimental work is to not only give the students a hands-on appreciation of building dynamics (natural frequencies of vibration, mode shapes, and damping), but also to build on their modeling skills. Thus it is useful to compare the experimentally obtained mode shapes with those of a well constructed computational model. In order to more precisely compare two mode shapes, a modal assurance criteria (MAC) [1] 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 to include the approximated mass matrix as a weighting factor. The mass-weighted MAC number for shapes Φ_i and Φ_j is given in Eq. 2:

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

The mass-weighted MAC number comparison between the experimental mode shapes and the computationally derived (by the authors) is given in table 2.

Table 2 Computational vs experimental mass-weighted MAC numbers

	Comp. Mode 1 (EW 2.44 Hz)	Comp. Mode 2 (NS 2.56 Hz)	Comp. Mode 3 (Rot. 3.23Hz)
Exp. Mode 1 (NS 3.61 Hz)	0.009	**0.722**	0.185
Exp. Mode 2 (EW 3.95 Hz)	**0.673**	0.094	0.216
Exp. Mode 3 (Rot. 4.61 Hz)	0.323	0.183	**0.600**

As can be seen in table 2, there is a clear correlation (>= 60%) between the computationally and experimentally derived mode shapes. Unfortunately, experimental mode shape 1 shows up as the second computational mode and experimental mode shape 2 shows up and the first. However, in both the experimental and computational results the frequency of vibration for modes 1 and 2 are close. Hence a relatively small change in the stiffness of the actual structure could indeed change the order of the modes.

A possible explanation can be found in the effect of the non-structural cladding. The building is twice as long in the EW direction as the NS. Thus it has more cladding in the EW direction than the NS. In the computational model, only the structural members are assumed to contribute to the lateral stiffness of the building. If the cladding were assumed to add some stiffness to the structure it would tend to stiffen the EW direction more than the NS. Thus the experimentally determined modes would show higher EW modal frequencies relative to the NS – as was observed. The authors are working on a more complex computational model in an effort to better quantify this phenomena.

With the aforementioned ordering difference, it can be concluded that the computationally derived modes agree reasonably well with the experimentally determined modes. Thus the theory and experimental procedures to determine a building's natural frequencies of vibration and the accompanying mode shapes and damping ratios is established with the students.

Student Experimental Laboratory

The next phase in the student exercise is to have the 24 students computationally model another campus building structure and predict the building's natural frequencies of vibration and mode shapes to the best of their current abilities. The students then apply the experimental method to obtain the actual natural frequencies but not the mode shapes. The mode shapes are determined by faculty and not revealed to students until later. Based on the actual building frequencies, the students will attempt to improve upon their computational models and again report their predicted frequencies and mode shapes. The student's estimates of frequencies and mode shapes before and after the experimental work are then compared to the actual experimental values. The purpose behind not revealing the actual mode shapes to the students until after they have revised their computational model is to replicate a common pitfall that catches many young engineers. That is, assuming they at least take the time to thoroughly check their results, a somewhat inexperienced engineer may tend to revise their model until the frequencies seem reasonable, but not bother determining if the resulting mode shapes seem appropriate.

To ensure a clean slate, a second campus building (Engineering West Building, see figure 7) was selected for the students to apply their experimental and analytical skills. The building is a two-story reinforced concrete shear wall structure. The floors and roof consist of a 4½-inch concrete slab supported by concrete encased steel wide flange sections. The building footprint is approximately 50 feet by 140 feet.

Figure 7: The experimental building

Students were tasked with predicting the first three natural frequencies of the building and the corresponding mode shapes using commercial structural analysis software[3] (see figure 8).

Students were also tasked with checking the results by hand to provide a reality check for the computer analysis predictions and the experimental results.

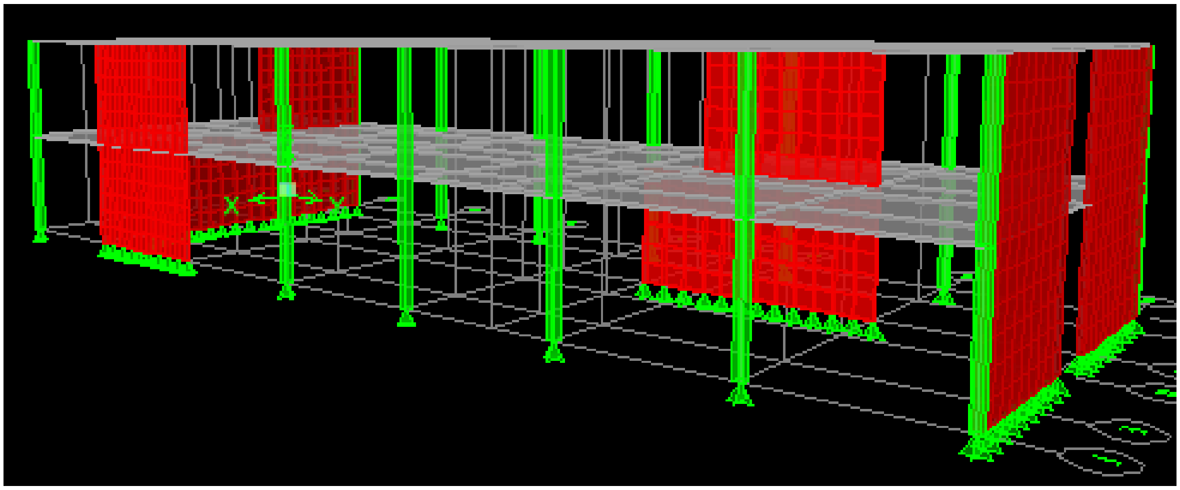

Figure 8: Student computer model.

A summary of the student predictions of the first three fundamental frequencies of the building using computer software are shown below in Table 3. For the 1st and 3rd modes the standard deviation was larger than the average fundamental frequency prediction. 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, particularly the implementation of these decisions within the software. In other words, while the students knew what they wanted in the model, they simply failed to achieve it. More importantly, they failed to check whether they had achieved it.

Table 3 – Student pre- and post-experiment fundamental frequency predictions (avg = average, σ = standard deviation)

	Experiment	**Student Computer Model Pre-Experiment**	**Student Computer Model Post-Experiment**
Mode 1 Frequency	5.3 hz	range = 0.5 hz – 47.1 hz avg = 8.0 hz; σ = 11.0 hz	range = 0.9 hz – 7.6 hz avg = 4.8 hz; σ = 1.2 hz
Mode 2 Frequency	6.4 hz	range = 0.6 hz – 29.4 hz avg = 8.5 hz; σ = 6.7 hz	range = 1.0 hz – 8.1 hz avg = 5.6 hz; σ = 1.4 hz
Mode 3 Frequency	6.95 hz	range = 0.7 hz – 78.2 hz avg = 16.8 hz; σ = 20.1 hz	range = 1.5 hz – 15.5 hz avg = 7.5 hz; σ = 2.8 hz

Following the student discussion of the modeling results, the class performed both ambient and forced vibration tests to determine the actual fundamental frequencies (see table 3). The students were also given the opportunity to redo the computer-based exercise in light of the test results. Of course they knew the correct answer from the vibration tests and it could be argued that knowing the answer ahead of time invalidates the results. However, most engineers should have a rough idea of the period of the modeled structure before creating a computer model.

The post-test results represent a significant improvement over the pre-test results (see table 3), clearly illustrated by the nearly 10-fold improvement in the standard deviation of the first fundamental frequency prediction. 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, member connections and boundary conditions. Secondly, for moderate discrepancies the students generally reviewed their input data more finely to search out incorrect member selection and mass assignment.

While the student prediction of the natural frequencies improved, their prediction of the mode shapes was nowhere near as impressive. Table 4 contains the average mass-weighted MAC numbers comparing the student's predicted mode shapes with the faculty determined experimental mode shapes. Clearly, prior to the experimental work the student predicted mode shapes had only fleeting correlation with reality. After the experimental work, the student's prediction of the modes certainly improved. However, at best their average correlation with the experimental shapes was only 35%. This can be compared to a well constructed computational model (prepared by the faculty) with correlations of 77% - 93%. Obviously the student mode shape predictions were poor – even after given an opportunity to improve their models.

Table 4 – Student pre- and post-experiment MAC numbers

	Student Computer Model Pre-Experiment	**Student Computer Model Post-Experiment**	**Faculty Computer Model**
Mode 1 MAC No.	0.23	0.35	0.93
Mode 2 MAC No.	0.12	0.22	0.90
Mode 3 MAC No.	0.09	0.31	0.77

Even though the overall student mode shape results were poor, there is some glimmer of hope. In the pre-experiment analyses less than 25% of the students created models where the first three modes were in the N/S, E/W, and rotational directions, respectively as determined by experiment. In the post-experiment analyses over 60% of the students created models where the first three modes were at least generally in the correct direction. Despite the MAC numbers improving by over 50%, the MAC numbers were still less than 0.5, the minimum threshold set by the authors for a reasonable correlation between the experimental and analytical results.

The lack of improvement in the student mode shape prediction versus the improvement in the frequency prediction can be explained by the fact that the students experimentally determined the fundamental frequencies for the building, but they did not experimentally determine the fundamental mode shapes for the building. Therefore, the students had experimental values to compare the fundamental frequencies, but no experimental results to compare the mode shapes. Future laboratories will include the students experimentally determining the mode shapes as well, with the expectation that the MAC numbers will improve post-experiment also.

Conclusions

The forced vibration testing procedure successfully found the natural frequencies, mode shapes and damping ratios of a building structure. With faculty guidance, the experimental procedure was executed by the students on two campus buildings. Student computational predictions of the building natural frequencies improved after observing the experimental natural frequencies. However, their predicted mode shapes left much to be desired. Student improvement of their computational models stopped when they obtained reasonable estimates of the frequency – the mode shapes were generally ignored. In future work the authors will investigate whether experimentally determining the mode shapes prior to revising computational models will actually result in improved student mode shape predictions. In other words, do the students possess the skills to improve their model's predicted mode shapes?

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