Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 396

FULL-SCALE, REAL-TIME BUILDING DYNAMICS LABORATORY

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ABSTRACT

Upon graduation, structural engineering students are often not able to create a sufficiently accurate computational model of a building. In the past few years, the authors have been developing a unique laboratory exercise to address this need by exposing students to full-scale, real-time experimentation of existing buildings on their university campus. 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 and then comparing their results to those from ambient and forced vibration tests of the building performed by the students themselves. In this paper, the procedure to experimentally determinate 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. A linear shaking device is employed to gently (below human perception) vibrate the building structure and highly sensitive (but inexpensive) hardware and software is employed to collect and process the results. Great care must be taken to properly position the equipment, filter out the extraneous data, and process and interpret the data. The result was found to be very enlightening for the students.

Introduction

Current approaches to engineering education have to some degree failed to prepare students to use computers effectively in engineering applications. Upon graduation, structural engineering students are often not able to create a sufficiently accurate computational model of a building. Accurately modeling the behavior of structures with computer software requires an understanding of the phenomenon being modeled as well as an understanding of the limitations of the computer analysis including the underlying assumptions. With the inevitable increase in the use of computers in engineering applications, a solution to this problem of inaccurate modeling is quickly needed.

In the past few years, the authors have been developing a unique laboratory exercise to address this need by exposing students to full-scale real-time experimentation of existing buildings on their university campus. Senior undergraduate students in their terminal analysis course were

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challenged with the task of predicting the natural frequencies and mode shapes of a building on campus using computer software and then comparing their results to those from ambient (Trifunac 1972) and forced vibration tests (Yu 2008) of the building performed by the students themselves. Previous efforts by the authors have focused solely on the natural periods (or frequencies) of vibration instead of the mode shapes (McDaniel 2009). The natural periods of a building were used at first because they are much more easily obtained experimentally than the mode shapes. However on occasion, students can make combinations of errors (intentional or otherwise) that force-fit the predicted periods to the actual periods of the building. This possibility is eliminated when both the mode shapes and periods are required. Furthermore, experimental and analytical observation of the mode shapes gives students a much deeper understanding of the structural behavior and the underlying structural dynamics theory. In order to assess the accuracy of their prediction of the mode shapes of the building the students compared results from: 1) hand calculations; 2) a computational model in current commercial software; 3) ambient vibrations tests; 4) forced vibration tests; and finally 5) the prediction of other classmates.

In this paper, the procedure to experimentally determinate 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. While in theory experimentally determining the mode shapes seems like an easy task, the reality is quite different. A linear shaking device is employed to gently (below human perception) vibrate the building structure and highly sensitive (but inexpensive) hardware and software is employed to collect and process the results. Great care must be taken to properly position the equipment, filter out the extraneous data, and process and interpret the data. The result was found to be very enlightening for the students.

Laboratory Description

The campus building selected for this exercise was the engineering building, Building 21 Unit #3 (see Fig. 1). The building is a two-story reinforced concrete shear wall structure with a basement in the east end of the building. 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. 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; and 3) the lateral resisting system (reinforced concrete shear walls) was visible and obvious.

The following simplifying assumptions were made by the students in their analyses:

1) The floors and roof were assumed to act as rigid diaphragms
2) Boundary conditions were simplified to either fixed or pinned connections
3) Uniform distribution of mass lumped at the diaphragm level
4) Material properties were not available on the drawings, typical values were assumed

Students were also asked to predict the first (highest) natural period of lateral vibration and first mode shape in each direction of the building using “hand” calculations and then again using the structural analysis software (see figure 1). 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 (CSI 2008).

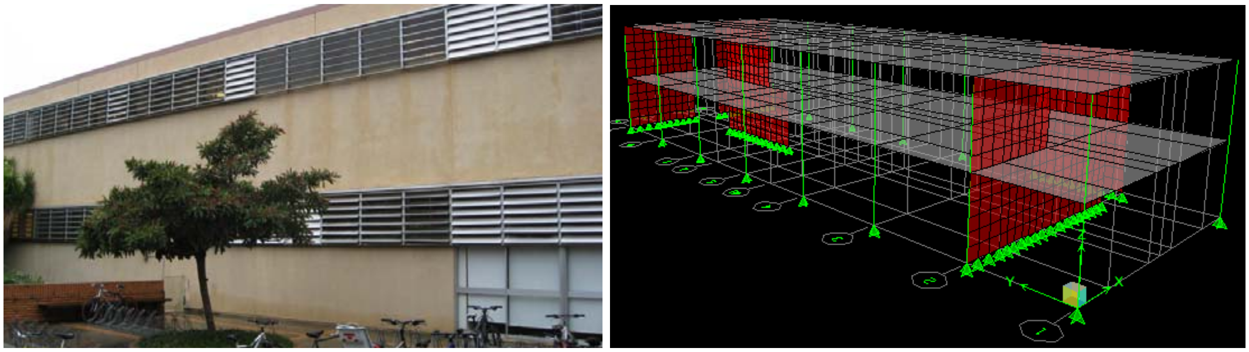


Figure 1: The experimental building and student computer model.

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 shaker 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. 2). 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. 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 excited at the natural frequency of the building to 50-500 µg when the shaker is excited at one of the buildings natural frequencies. These magnitudes can be compared to ambient accelerations, within the range of building natural frequencies that are 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.

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.

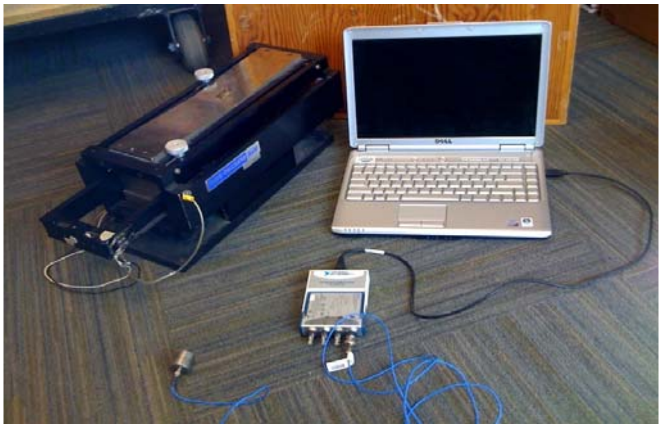


Figure 2: Test equipment (shaker, accelerometer, DAQ, computer).

The digitized data streams from the accelerometers were processed using standard lab software (MathWorks Inc. 2009). 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 x, y, and rotations. The peaks in the FFT plot are extracted and displayed on screen to aid in the data collection.

Ambient Vibration Test

To provide a baseline, the students performed an ambient vibration test (AVT) by placing three accelerometers on the floor of the 2nd floor student laboratory in the South-East 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 EW direction but spaced 16 feet from the first to provide floor rotations. An FFT plot of the results is shown in figure 4. 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 by nature 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 (5.4 Hz and 6.9 Hz) and one peak in the EW direction (6.4 Hz). There is also one minor peak in the NS and in the EW data. The rotation data shows no clear peaks. The major peaks likely represent the natural frequencies of vibration of the building structure. Unfortunately the peaks are not distinct and the actual natural frequencies could easily lie up to 0.2 Hz away from the estimate. Still, the ambient vibration data does provide an easily obtained estimate of the natural frequencies and valuable directions for further investigation.

Based on the results of the AVT, the students placed the shaker in a SW to NE direction on the floor of second floor laboratory (in the SE 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.

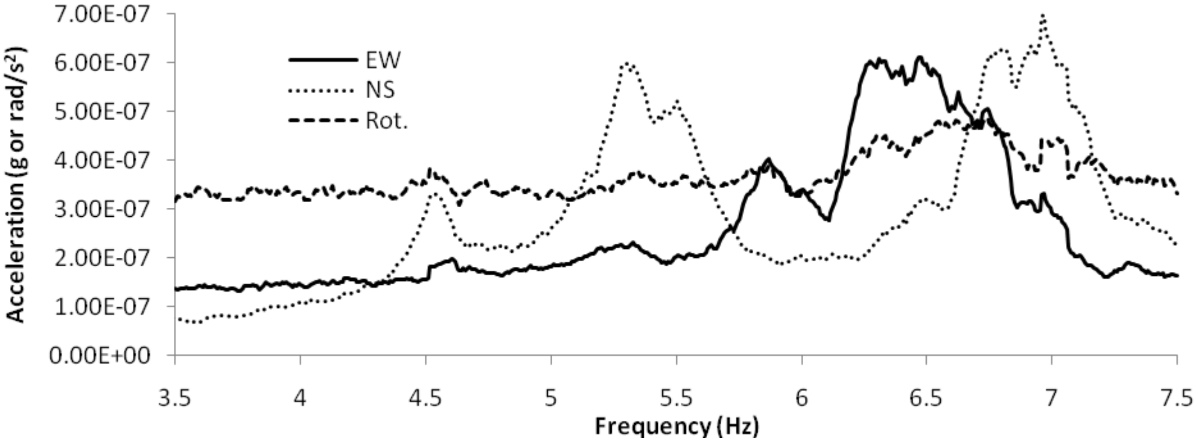


Figure 3: Ambient vibration response.

Forced Vibration Test

An FFT plot of the forced vibration test (FVT) results is shown in figure 5. 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 5.3 Hz the FFT result in the NS direction is 1.4 μg. If the shaker remains at 5.3 Hz for the entire 120s window the result is 42 μg.

Figure 4 shows 3 distinct peaks indicating the first three natural frequencies of vibration (5.3, 6.4, and 6.95 Hz). A comparison with the AVT results (figure 4) demonstrates that even the very low excitation of the shaker has not only cleaned up the broad peaks in the AVT but has also produced a response for the rotational accelerations. At 5.3 Hz, the motion is primarily in the NS direction with some minor motion in the rotations and EW direction. The second mode occurs at 6.4 Hz and is strongly in the EW direction with some rotation. At the third mode (6.95 Hz) the motion appears entirely in the NS direction.

Looks however can be deceiving. Recall that all three FVT plots are the result of one shaker placement in the SE 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, 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 for the third mode it appears that the shape is entirely in the NS direction, in reality it is that 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.

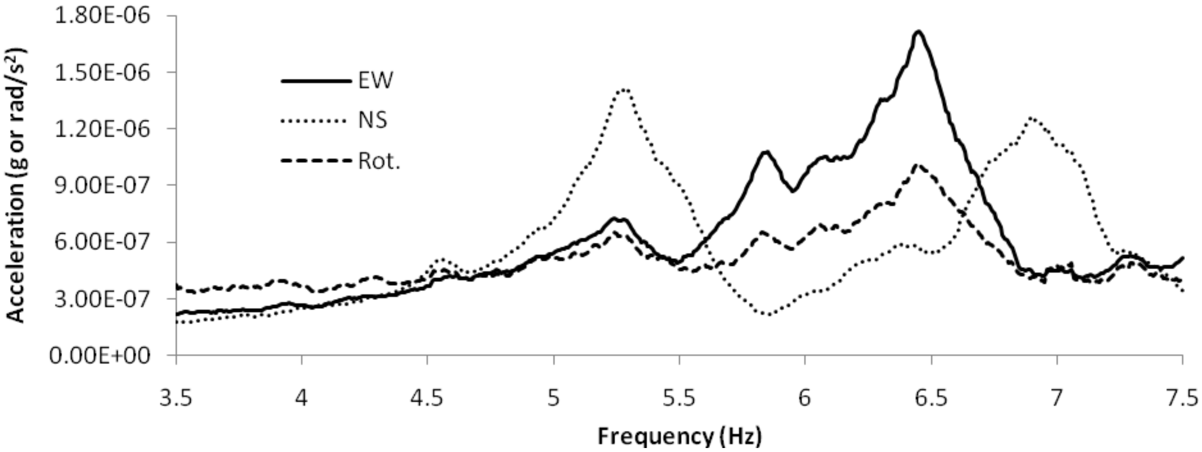


Figure 4: Forced vibration response.

The damping ratio for each mode is found using the half-power band method described in the course textbook (Chopra 2007) directly from the FVT shown in figure 5. For example, the frequencies that correspond to 0.707 times the peak response (at 6.4 Hz) are 6.15 and 6.59 Hz. Thus the damping ratio for the second mode is 3.4%. The first and third mode damping ratios were similarly found to be 3.4% and 3.6% respectively.

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 to the approximate center of mass of the floor slab.

For mode 1, the FVT test indicated a strong NS component with much weaker EW and rotational components. Thus the shaker was run at 5.3 Hz and placed in the NS direction at the approximate center of mass. The measured accelerations are given in table 1. As predicted by the FVT, the motion is primarily NS with some minor EW and rotational acceleration. At mode 2, the FVT shows primary EW motion with some rotation. Curiously though, when the shaker was placed in the EW direction at the center of mass, the rotational accelerations fell to zero. Clearly the rotational component in the FVT was an erroneous contribution from another mode. For the third mode, the FVT predicted a strong NS component and little EW or rotational motion. However, when the shaker was run at 6.95 Hz and was placed at the center of mass in the NS or the EW direction, minimal accelerations were measured in all directions. This indicates a primarily rotational mode about the center of mass. Thus the shaker was moved back to the SE corner of the building and placed in a SW to NE direction and run at 6.95 Hz. This produced the modest accelerations shown in Table 1.

The raw accelerations shown in table 1 can be easily misconstrued. For each mode, the shaker was placed in a different orientation. Thus, even though the shaker load was kept constant at 30 lb, 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 center of mass can be constructed assuming a uniform density for the floor slab as $M = diag\left[\rho bh \quad \rho bh \quad \frac{\rho bh}{12}(b^2 + h^2)\right]$, where b and h are the length and width of the building respectively and ρ is the mass per area of the floor slab.

Table 1. Acceleration Readings at Center of Mass

Mode	EW (μg)	NS (μg)	Rot. (μ rad/s^2)
1 (5.3 Hz)	12.71	53.86	3.221
2 (6.4 Hz)	108.2	15.39	0
3 (6.95 Hz)	27.32	12.13	-9.567

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) (Golub 1989) algorithm is used to sweep the unwanted modes out. For example, to sweep mode 1 (ϕ_1) out of mode 2 (ϕ_2):

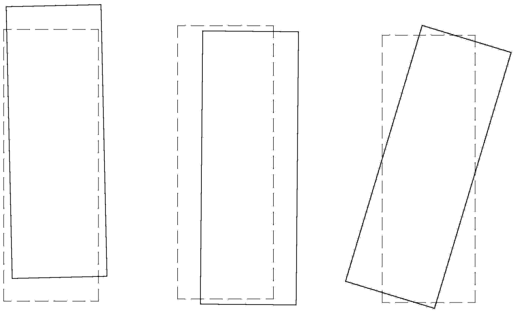
$$\phi_2' = \phi_2 - \frac{\phi_1^T M \phi_2}{\phi_1^T M \phi_1}\phi_1 \qquad (1)$$

Unfortunately, in order to apply this process, one needs a clean mode shape to start sweeping out the other mode. Since a pure mode shape is not available, an approximate starting point must be assumed. In this case mode 1 was chosen since its natural frequency is slightly more separated from the others. However mode 2 would have made an acceptable choice as well since it is predominately an EW motion. Using mode 1 as the base, the orthogonalized (and normalized) mode shapes are shown in table 2.

Table 2. Orthonormalized Accelerations at Center of Mass

Mode	EW (ft/s^2)	NS (ft/s^2)	Rot. (rad/s^2)
1 (5.3 Hz)	2,824	11,968	22.23
2 (6.4 Hz)	12,003	-2,805	-8.671
3 (6.9 Hz)	-141	990	-293.3

After the orthonormalizing process, it is clear that modes 1, 2, and 3 are primarily NS, EW, and rotational, respectively. The mode shapes are plotted in a plan view in figure 5. 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) (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 to include the approximated mass matrix as a weighting factor.



North-South East-West Rotation

Figure 5. Experimentally determined mode shapes.

The mass-weighted MAC number for shapes ϕ_i and ϕ_j is given in Eq. 2:

$$\mathrm{MAC}_{ij} = \frac{(\phi_i^T M \phi_j)^2}{(\phi_i^T M \phi_i)(\phi_j^T M \phi_j)} \tag{2}$$

The mass-weighted MAC number comparison between the experimental mode shapes and the computationally derived (by the authors) mode shapes 1, 2, and 3 is 0.93, 0.90, and 0.77, respectively. Modes 1 and 2 show an excellent correlation -- mode 3 slightly less so.

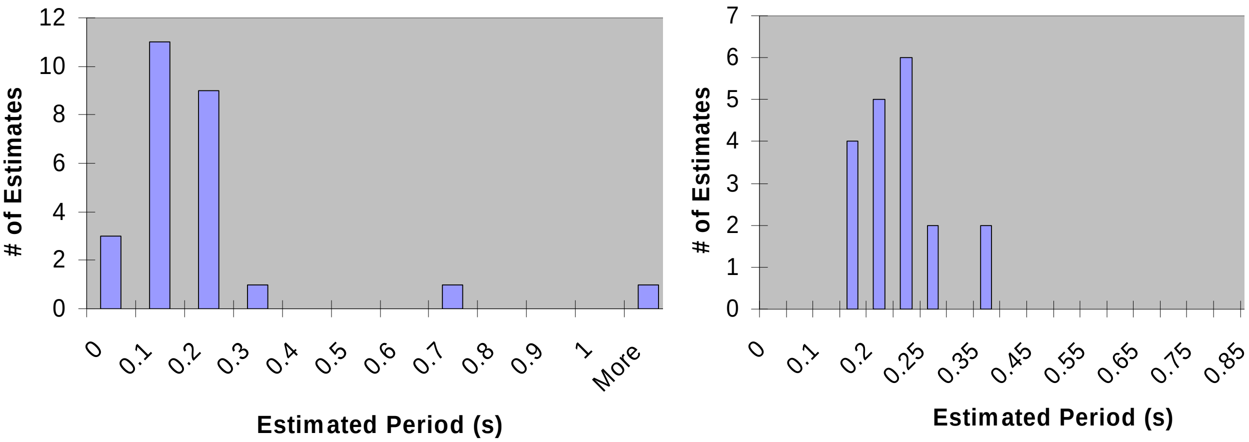
Student Modeling Results

The results of the student predictions of the fundamental period of the building using computer software ranged from a low of 0.01s to a high of 2s. The median value for the computer calculations was 0.23s with a standard deviation of 0.4s. The MAC numbers for the first 3 fundamental mode shapes were 0.6, 0.4 and 0.5, respectively. 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. While their modeling decisions were generally good, it was the implementation of these decisions within the software that caused the most variation in the predictions. 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.

Following the student discussion of the modeling results, the class walked over to the building to perform both ambient and forced vibration tests to determine the actual period of vibration (see figure 4). As can be seen, the lowest dominant frequency obtained was 5.3 Hz. This corresponds to a period of vibration of 0.19s. The fundamental period of vibration will vary as the amplitude of the forced vibration increases (Celebi 1993), however, no significant variation was measured under forced vibrations up to 40 times the ambient vibrations.

Upon performing the ambient vibration test and confirming the period of vibration, the students were somewhat stunned and embarrassed; they were shocked that "the computer gave them incorrect results". The students were given the opportunity to redo the computer-based exercise in light of the test results. Of course they knew the correct answer from the ambient vibration test and 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 histogram of the student computer-based revised predictions of the natural period of vibration is given in figure 6.



(a) (b)

Figure 6. (a) Pre-test computer-based results; (b) Post-test computer-based results

As can be seen, the results represent a dramatic improvement. The median result was 0.21s, with a standard deviation of only 0.05s, almost a 10-fold improvement over the standard deviation calculated before the experimentation. 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. 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. While the prediction of the natural frequencies improved dramatically, the prediction of the mode shapes did not. The resulting MAC numbers varied little from the pre-test analyses. Future research will focus on how to improve student prediction of both the fundamental frequencies and mode shapes of buildings.

Conclusions

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. Furthermore, the laboratory work brought to life the theory of structural vibrations presented in the lectures. It provided them with tangible evidence that "real-world" buildings respond according to the natural modes of vibration. By both theoretically and actually applying a sinusoidal load to a multi-degree-of-freedom structure, the students were forced to simultaneously consider the mathematical and physical results. The work helped remove the typical disconnect in the student's minds between theory and practice.

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