AC 2011-129: EXPERIMENTAL EXPLORATION OF COMMON MODELING ASSUMPTIONS

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Experimental Exploration of Common Modeling Assumptions

Abstract

The goal of this exercise is to expose undergraduate engineering students to the effect of their computational modeling decisions on the predicted dynamic behavior of structural systems. This work is part of an ongoing effort to create a series of full-scale, low-cost experimental exercises aimed at improving student learning of Mechanical Vibrations. This particular exercise focuses on the common assumption that building floor and roof diaphragms are rigid. An assessment of the building diaphragm rigidity was performed by the students using Forced Vibration Testing of a campus building. In this experiment, the students determined the natural frequencies and mode shapes of the buildings. In current building codes, diaphragms with aspect ratios less than three are permitted to be idealized as rigid. The case study building fell within this boundary. However, the students determined that the building's diaphragm exhibited semi-flexible behavior. The students also created simple hand calculation models and detailed computational models which confirmed the experimental results. The predicted story drift for the building was significantly higher when modeled with a semi-rigid diaphragm. When surveyed, the students indicated that the exercise had greatly increased their awareness of how modeling assumptions affect the final results. In particular they will be far less accepting of simplified building diaphragm modeling for structures sensitive to story drift demand limits.

Introduction

As part of their final analysis course (ARCE 483 Seismic Analysis and Design), Architectural Engineering students at California State University, San Luis Obispo, were given the opportunity to conduct forced vibration experimentation on a building on campus as well as predict the dynamic response of the building. The goal of this exercise is to expose undergraduate engineering students to the effect of their modeling decisions on their prediction of the dynamic behavior of structural systems, a task they will soon be charged with as practicing engineers. This work is part of an ongoing effort to create a series of full-scale, low-cost experimental exercises aimed at improving student learning of mechanical vibrations. This particular exercise focuses on the common assumption that building floor and roof diaphragms are rigid.

Since most mechanical vibrations problems are analyzed using a computer, another focus of this exercise is to build student skepticism for their computer models. Since students lack the experience required to develop engineering intuition, they need the tools to determine if their computer analysis results are reasonable. Unfortunately, students are often unsure of how to apply their undergraduate education to check computer output. Therefore, the students are first tasked with performing simple hand calculations to check their computer analysis predictions. By moving from simple models to increasingly complex models, students are able to see the effect of the assumptions in each model.

Case Study

The students investigated Unit 5 of the Engineering West Building 21 (EWB Unit 5) located on the campus of California Polytechnic State University, San Luis Obispo (see Figure 1). The two-story building is rectangular in plan with dimensions of 60′ in the north-south (short) direction and 160′ in the east-west (long) direction. The floor and roof diaphragms are 4½" thick concrete slabs. The shear walls in the north-south direction are composed of reinforced masonry. The shear wall in the east-west direction is composed of reinforced concrete. After reviewing the plans for the building, the students walked through and around the building to gain a better perspective on the building design and construction.

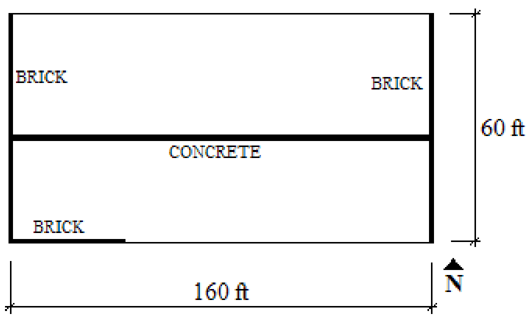

Figure 1: EWB Unit 5 a) Plan b) Elevation

Student Buidling Model Hand Calculations

The first exercise for the students was to create a very simple model to capture the building behavior, specifically the building fundamental frequency in the short direction. The purpose of this exercise was to get the students to explore the building lateral system on a macro level and obtain a ballpark estimate to guide further modeling. Students have the tendancy to start with far too detailed models and often continue to increase the level of complexity. In doing so, students often bypass conceptualizing the basic structural behavior. As a result, the students have difficulty understanding their complex model results; if the students are aware of errors in the first place. This first model created by the students was a single-degree-of-freedom (SDOF) “lollipop” model with the total building mass lumped at the roof (see Figure 2) and the stiffness based on the shear and flexural stiffness of the cantilever brick shear walls. The stiffness of the nonstructural members was ignored. This model provided a temporary lower bound for the fundamental frequency prediction of 8.9 hz. Since the shear walls were dominated by shear rather than flexure this lower bound prediction is not as conservative as it would be for a lateral system that is dominated by flexure such as a moment frame.

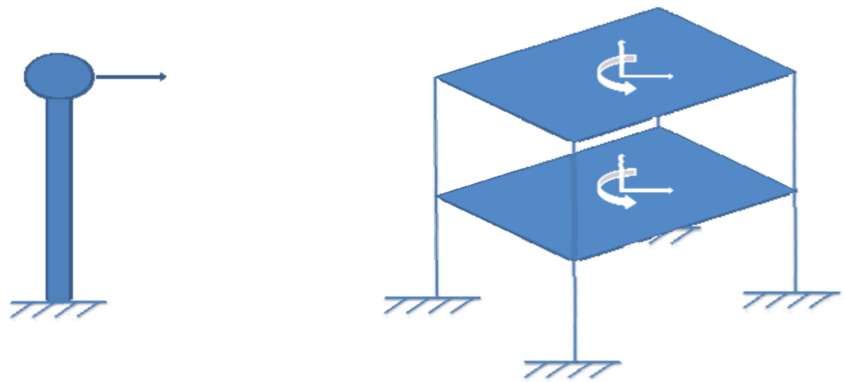

Figure 2 a) SDOF hand calculation model; b) MDOF hand calculation model

The second exercise for the students was to create a multiple-degree-of-freedom (MDOF) model with a rigid slab assumption and 3 DOF's per floor (see Figure 2) using Matlab[6]. The mass was lumped at each floor and the stiffness of each story was based on the shear wall shear and flexural stiffness assuming double bending behavior. This provided an upper bound estimate of the building fundamental frequency of 11.4 hz as well as estimates for the additional 5 modes. This more complex hand calculation illustrated to the students how the short, long and rotational frequencies relate and interact with one another.

Student Computational Model

The third exercise for the students was to create a computational model using commercial structural analysis software, ETABS[3]. Based on the building aspect ratios, the design code (ASCE 7-05[1]) allows for the use of a rigid diaphragm to model the building. The reason the hand calculations preceeded the computational model was to provide a basis for comparison and to identify errors in the more complex computational model. This proved very beneficial since initial computational model predictions by the students were off by as much as a factor of 10. Similar to the MDOF hand calculations the mass was lumped at each story computational model. The lateral system included only the shear walls, ignoring the stiffness of the nonstructural elements. A student computational model of EWB Unit 5 is shown in Figure 3. The student computational model fundamental frequency prediction was 10.4 Hz.

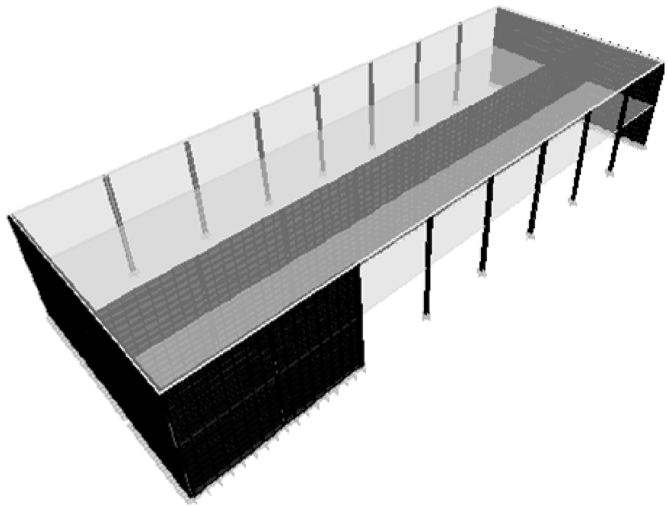

Figure 3: EWB Unit 5 Student Computational Model

Forced Vibration Test

While computational modeling provides students with predictions of building behavior, the authors have found that providing students with the experience of testing an actual building enhances student learning and retention dramatically[7,8,9]. Thus the next phase of the student exercise is to physically shake the campus building and record the resulting motions. Clearly it would be inappropriate to damage a lecture hall or even disrupt lectures in progress. Thus the shaking of the building is done far below the level of human perception instead of a typical large shaker setup[11].

Figure 4: Test Equipment at Rest and at Work

The test equipment (see figure 4) consists of a small portable 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. 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[4,7,8,9] that when appropriately placed in low-rise structures, the shaker can induce motions detectable throughout the building on all floors.

To determine the natural frequencies of the building the students place the shaker on the floor of the top story corridor and record the resulting building accelerations. At most shaker frequencies the building responds minimally. However when the shaker frequency matches a natural building frequency, resonance is achieved and the building accelerations spike dramatically. The student results are plotted in figure 5. Two significant peaks are observed, one at 5.3 Hz and one at 9.2 Hz. These correspond to the first and second natural frequencies of the building structure. The students noted that both modes were primarily in the North-South direction, *i.e.* the short building direction, with some minor rotational contribution. As predicted by the student's computational model, no natural frequency with a significant component in the long building direction was found in the range tested.

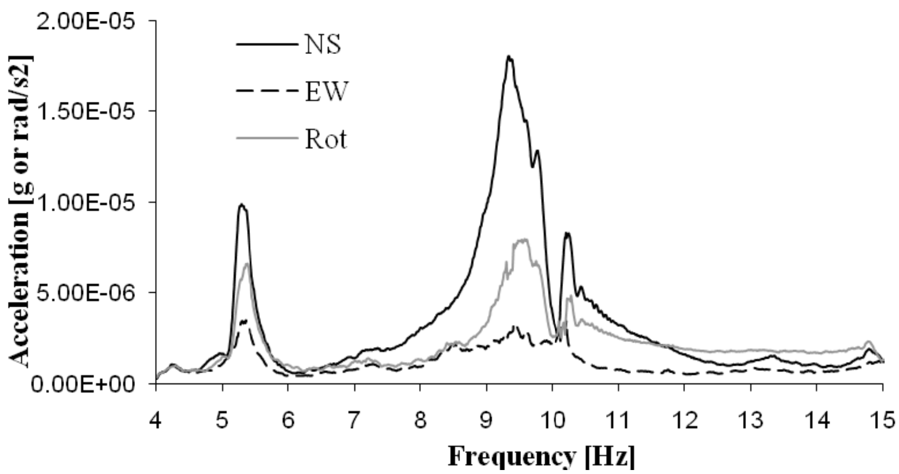

Figure 5: Forced Vibration Testing Results

The students and even some faculty members were skeptical that such a small shaker could produce measurable accelerations in a nearly 2,000 ton building. Thus the students were directed to use their computational model and analytically apply a 30 pounds sinusoidal load and predict the second floor response using hand calculations. This is typical structural dynamics problem found in many textbooks[2,5]. Using a damping value of 1.7% found from previous work[10] the students predicted an average building response of approximately 200 μg. This agrees well with their experimentally determined value of 233 μg. This exercise gave the students confidence in both their experimental method and their analytical models.

Comparison of frequencies

The students were asked to compare their analytical predictions for the first natural building frequency 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 10.4 Hz. Since their 6-DOF hand calculation model additionally stiffened the walls (by enforcing that plane sections remain plane), the prediction was higher still – 11.4 Hz. Finally, since their SDOF model lumped the building mass at the roof level, the SDOF model produced a somewhat lower estimate (8.9 Hz) in comparison with the 6-DOF model. Through this process, the students determined that they needed to choose the semi-rigid diaphgram option in ETABS to incorporate the diaphragm flexibility. The resulting fundamental frequency for the their semi-rigid diaphragm computational model was 5.6 Hz. This prediction compared very closely with the experimental result of 5.3 Hz. From this comparison the students not only learned a valuable lesson with regards to the modeling of floor and roof diaphragms. They also gained significant insight into the effect of wall and building mass modeling on predicted behavior.

Mode Shapes

The next phase of the exercise is to have the students experimentally determine the shape (mode shape) the building takes on as it vibrates in its first natural frequency. To accomplish this, the students set the shaker running at the building's first natural frequency and then placed the accelerometer at various points down the second story corridor. A normalized graph of the resulting measured accelerations represents the first natural mode shape of the building. The student results for the experimentally derived mode shape are shown in Figure 6 along with their results for their rigid and semi-rigid diaphragm models.

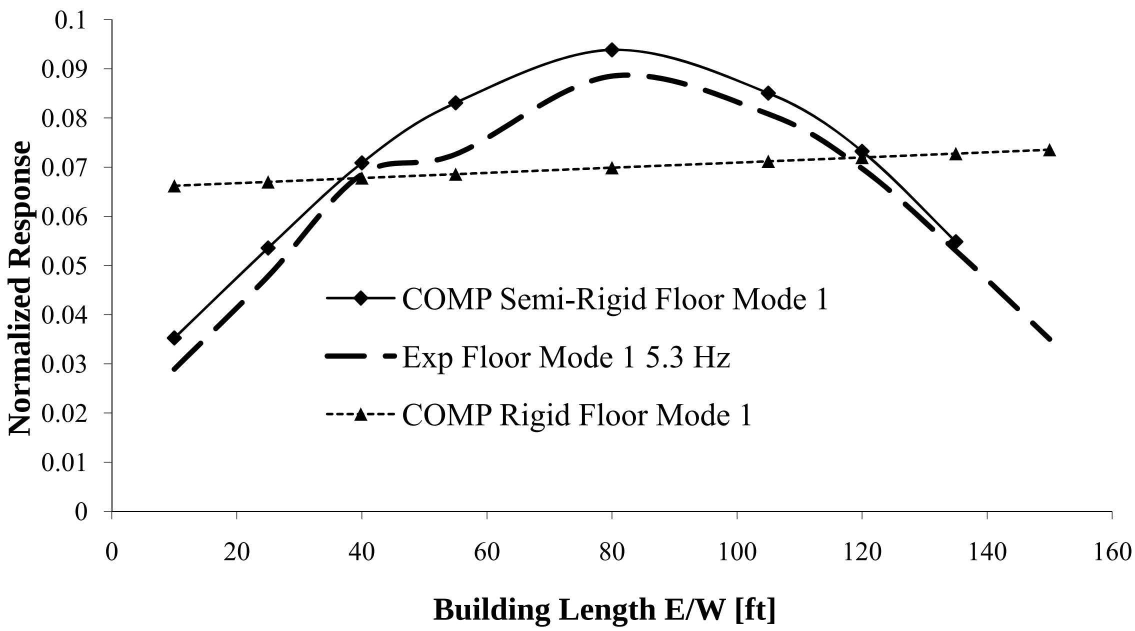

Figure 6: Mode Shape Comparison

From Figure 6, the students rightfully concluded that only their semi-rigid diaphragm model reasonably captured the behavior of the building. Their rigid diaphragm model, and by extension their hand calculation models results, failed to capture the actual behavior. This observation is well supported by the accuracy of the modal frequency results.

Design Implications

The students came to the conclusion that the rigid diaphragm model permitted in the code[1] produced poor estimates of the building natural frequency and mode shapes. To put this result in context, the students were asked to determine how or if the modeling decisions could affect the design of the building in terms of base shear (total lateral force for which the building must be designed), and story drift (movement of the roof relative to the floor). The students found that for any given earthquake, the rigid and semi-rigid diaphragm models could produce large variations in base shear. However, since the design spectrum in the code represents the predicted effect of any future earthquake and both models predicted a relatively high natural frequency, there was negligible difference in the two base shear values. Their predicted story drifts were under-predicted in the rigid diaphragm models by 200-300%. However the semi-rigid diaphragm model results were still within the limits prescribed by the code.

Conclusions - Lessons Learned

This exercise provided the students with a hands-on learning environment that challenged them to apply concepts and techniques from several courses to one practical, real-world case study. The process of developing increasingly more detailed computational models and comparing to their full-scale testing results imparted a deeper understanding not only of structural behavior but also the role of modeling in structural design. Through the use of physical testing, the students were able to observe the predictions of their models and make more intelligent decisions regarding the appropriateness of the model. Armed with their validated model, the students were then able to put building code simplifications with respect to floor and roof diaphragms into context and understand how the simplifications affect their designs. When surveyed, the students indicated that the exercise had greatly increased their awareness of how modeling assumptions affect the final results. In particular they will be far less accepting of simplified building diaphragm modeling for structures sensitive to story drift demand limits.

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