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Teaching Modal Analysis with Mobile Devices

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Abstract

An inexpensive system capable of performing modal analysis of laboratory models and full-scale structures was employed in both a laboratory and field experience in a 400/500-level bridge rating elective course. The system, comprised of an electromechanical shaker and an array of 12 iPods, allows for an introduction to modal testing of bridges and other structures in an active and highly physical way. A laboratory module employing the system is described. Indirect and direct assessment of student learning is reported along with student evaluation of the module. In general, students perceived full-scale testing, numerical modeling, and discussion of theory as more valuable than lab-scale testing in supporting their learning. Their confidence in demonstrating their understanding was high for lower-cognitive-level objectives and lower for application-level objectives. Their ability to demonstrate their learning was relatively inconsistent with their own perceptions of their ability. Given the demonstrated learning and high perceived value of full-scale field testing, the effort to deploy a shaker and relatively simple data collection system using mobile devices was deemed an effective way of introducing students to experimental modal analysis and resonance testing.

Introduction

Modal analysis of highway bridges to support refined analysis, condition rating, and load rating is an evolving field of research, with departments of transportation and university research groups leveraging technology to produce more efficient and effective systems capable of being deployed more widely to support structural health monitoring and resiliency efforts. Introducing students to methods and applications in the dynamic evaluation of structures is an important part of the graduate-level structural engineering curriculum at Oregon Institute of Technology. While the equipment required to conduct modal testing of civil structures can be costly, accurate and precise measurements can be collected, post-processed, and visualized with mobile devices and apps that can access the ubiquitous on-board 3-axis accelerometers. With sampling rates of 100 Hz and sensitivities to the 0.0001 g these devices provide a cost-effective means of conducting dynamic measurement, post-processing, and data acquisition for both education and engineering practice.

The goals of modal analysis are to determine modal frequencies and associated mode shapes, which can be related to structural parameters like support conditions, material and geometric stiffness, and dead load distribution. With most of these parameters well described, the lesser known of them can be accurately estimated for simple systems. Further, modal frequencies and mode shapes can be used to validate numerical models to improve the accuracy of more refined structural analysis efforts for complex structural systems. Experimental modal analysis has been conducted on bridges traditionally using single-input multiple-output (SIMO), multiple-input multiple-output (MIMO), or output-only methods, where inputs refer to dynamic excitation by impact or harmonic forcing and outputs are displacements or accelerations generally measured at a resolution necessary to accurately describe a mode shape. The most popular methods use an instrumented hammer, impactor, or harmonic exciter and an array of wired or wireless accelerometers [1].

Cole McDaniel and others at Cal Poly [2,3] have long used electromechanical shakers to demonstrate principles of dynamic structural response in the classroom and in full-scale buildings. Hopfner et al [4] described how mobile devices could be used to measure mechanical vibrations. Others have used mobile devices to teach principles of structural damage detection [5] and have identified mobile devices as a potential means to crowdsource structural response data for to support learning activities as well as infrastructure management [6]. Some researchers are finding that mobile devices may serve as effective data collection tools in the field [6,7,8]. With respect to teaching experimental modal analysis to undergraduates, Peter Avitabile [9] described the value of color and multimedia but did not address laboratory or field experimentation. Avitabile emphasized that modal analysis is a topic that generally requires multiple graduate-level courses to master.

The author of this study sought a means of using ambient and forced vibration methods with an array of mobile devices (iPods) to conduct modal testing in both the laboratory and the field to introduce students to modal analysis, refined methods of analysis, and dynamic load testing to support bridge condition and load rating efforts. This paper will describe an educational module and the results of assessment of student learning and perceptions of the module.

Conduct of the Module

The module consisted of a 50-minute class period and a 3-hour lab period. The class period was used to introduce the dynamic behavior of a single-span beam on simple supports, while the lab period consisted of forced vibration testing of a 3-span pedestrian walkway in a campus building. The activity is described in a handout provided to students, which is reproduced in Figure 1.

Class Activity

The 50-minute class activity consisted of a brief board-based introduction to mode shapes and natural frequencies for a single-span beam on simple supports. Students then joined one of three groups to (1) develop a numerical model of the beam, (2) test a physical beam with mobile devices using imposed displacements and free vibration, and (3) calculate the natural frequencies associated with the first three modes of vibration using closed-form analytical solutions to the governing differential equation. Once each group had completed their task, the last five minutes of the class were used to compare and discuss the collective results.

A board-based introduction to the concepts began with a discussion of vibrating strings and related them to vibrating beams (Figure 2). The first three mode shapes for a uniformly loaded, simply supported beam were drawn and the equation for the natural frequencies of such a system was provided. Via questioning, students generated a list of the structural parameters that influence the natural frequency (clearly those variables present in the solution). At this point, the three teams were formed quickly and their tasks described only verbally. The instructor worked with each team individually as needed to ensure timely progress. The work of the numerical modeling, physical testing, and analytical calculation groups will be described in the following subsections.

Week 9 – Field Testing of Bridges: Forced Vibration Analysis

Learning Objectives

1. Define natural frequency
2. Explain how mode shapes and natural frequencies are related to fundamental structural parameters including dead load distribution, section properties, stiffness, and support constraints
3. Explain how dynamic response measurements can be used to conduct refined condition and load rating of bridges
4. Use dynamic response measurements to validate a numerical model
5. Explain how to conduct a refined rating of a bridge using an appropriate structural analysis method
6. Describe the differences between analytical methods, girder line analysis, a grillage analysis, and a 3D finite element analysis

Class Activity

Compare the measured frequencies and modes for an easily modeled and well-behaved prismatic steel beam to those produced by a numerical model (use Mastan) and a closed-form analytical solution.

Lab Activity

1. Prepare an a priori numerical model (use Mastan) to estimate the natural frequencies and modes for the three-span bridge walkway between the east and west wings of the Dow Center for Health Professions. Plot the frequencies and mode shapes for the structure prior to visiting it.
2. Conduct periodic impact and harmonically forced vibration testing of the structure, attempting to determine as many mode shapes and frequencies as possible.
   a. Begin by subjecting the structure to a periodic impact and measure the dominant frequencies using the VibSensor app at anticipated modal antinodes (locations of maximum displacement).
   b. After determining the frequencies and mode shapes, estimate the locations of modal antinodes and place the shaker at those locations and force at the corresponding natural frequency to induce resonance. Ensure you have discovered a resonant frequency by adjusting the frequency of vibration to identify a maximum response acceleration. Measure the mode shape using the iPods.
3. Revisit your numerical model to make reasonable adjustments to dead loads, section properties and support constraints in order to achieve the observed frequencies and mode shapes.
4. Consider how you could improve your numerical model to more accurately model the behavior of the Dow bridge. Discuss which parameters are most uncertain and how you might better determine properties of the bridge or identify damage or deterioration in the structure.

HW7 Assignment (due Wednesday week 10 by 6pm):

Prepare a memorandum that describes the procedure and results of the laboratory testing. Discuss the significance of the results and the potential sources of error and reasons for inconsistency, as well as addressing all points in the lab activity description above.

Figure 1. Handout describing class and laboratory activities for the modal analysis module.

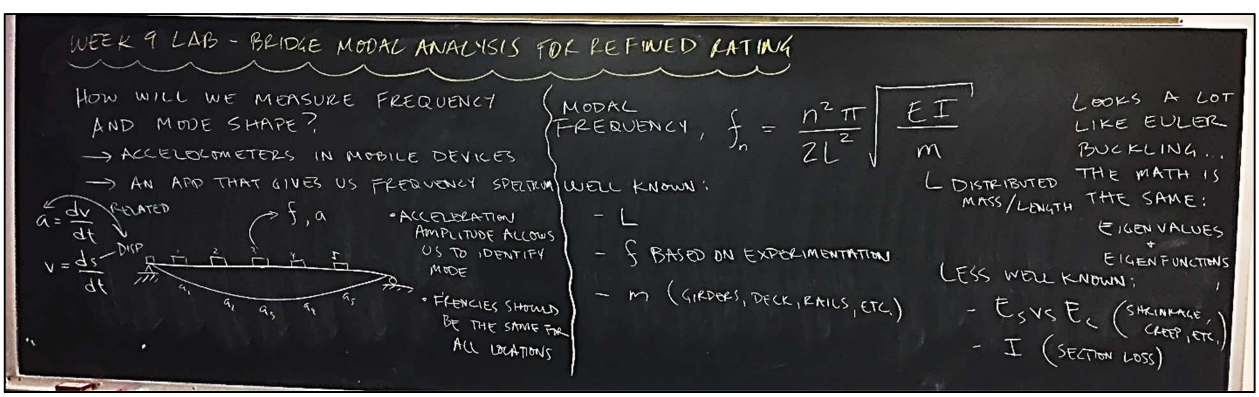

Figure 2. Introduction board for bridge modal analysis module.

Numerical Modeling Group

The numerical modeling group gathered around a laptop computer to develop a simple beam model in MASTAN2, a free matrix structural analysis package that includes an eigensolver [10]. The team attempted to work with the software without significant orientation to the program (although they had previous experience with structural modeling in other packages) and were told to simply model the beam and identify the first three natural frequencies. The students began by creating two nodes and a single element, specifying the span, cross section, and material properties measured by the physical testing group, imposing simple supports, and running a natural frequency analysis. It was clear that the result was not reasonable and the instructor queried the students as to why this might be, specifically how mass was likely handled in the solution. After a brief discussion of matrix methods and lumped masses, the students subdivided the single element into 12 sub-elements and were able to produce a more reasonable first natural frequency (Figure 3) as well as the second and third frequencies and their associated mode shapes (Figures 4 and 5). The group recorded their results on the chalkboard (see right side of board, Figure 7).

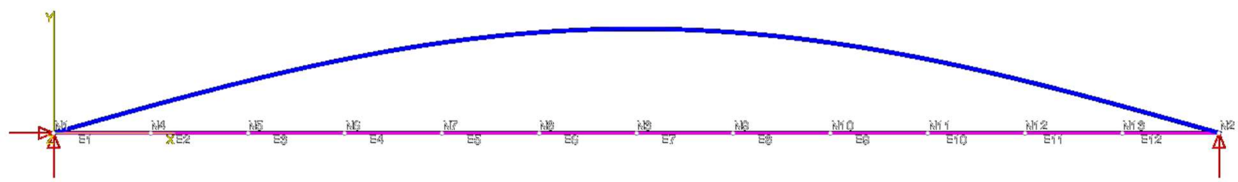

Figure 3. First mode of modeled prismatic beam (T = 0.09526 sec, *f* = 10.50 Hz).

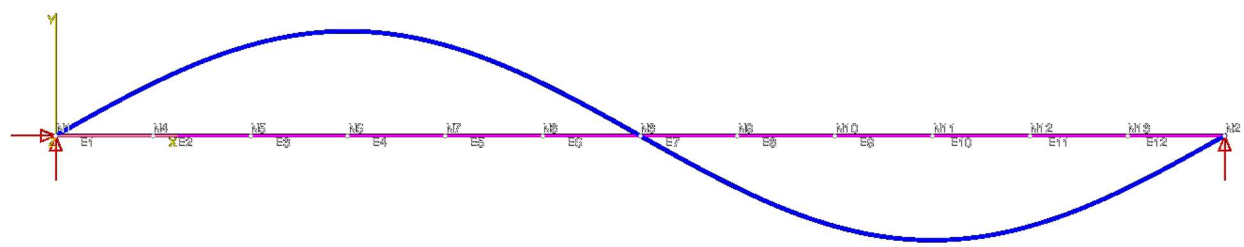

Figure 4. Second mode of modeled prismatic beam (T = 0.023807 sec, *f* = 42.00 Hz)

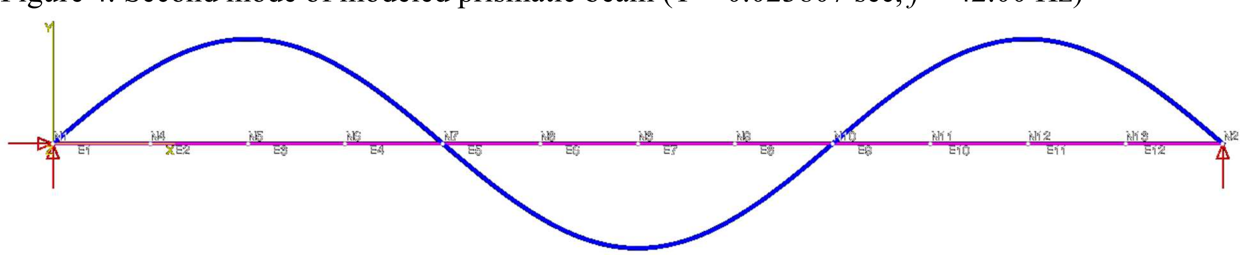

Figure 5. Third mode of modeled prismatic beam (T = 0.010584 sec, *f* = 94.48 Hz)

Physical Testing Group

The physical testing group set to work with the nominal 6-in by 3/8-in steel beam oriented flat with a span of 56 in (Figure 6).

Figure 6. Simply supported prismatic steel beam with iPods placed for vibration measurement.

After a brief discussion of where to place iPods in order observe each expected mode shape (see left side of board, Figure 7), the students chose nodes and antinodes of the first three modes, specifically quarter and sixth points along the span. The iPods were running an app called Vibration Analysis [11,12], which produces a real-time frequency spectrum with a 10-second window (see Figure 8). Thus, dominant frequencies can be identified along with the amplitude of acceleration in units of g. With the beam set to vibrate freely, the array of iPods clearly displayed similar frequencies (10.33-10.40 Hz) and amplitudes that approximated the first mode shape with a maximum at mid-span and noise registered at the supports. After attempting to force the second mode with an imposed displacement (rubber mallet strike) at the second mode antinode (i.e. quarter point), the students added a support at mid-span to ensure the second mode was dominant. The iPods displayed similar frequencies (38.43-39.40 Hz) and amplitudes consistent with a full sine wave (Figure 9). Finally, the third mode was forced by adding supports at the third points. iPods displayed a dominant frequency of 3.33 Hz, the result of aliasing, which occurs when the signal frequency is greater than the Nyquist frequency (50 Hz), defined as half the sample frequency (100 Hz for iPods). The actual signal frequency can be calculated by subtracting the alias frequency from the closest integer multiple of the sampling frequency (100 – 3.33 = 96.67 Hz) [13]. Each of the measured values compared remarkably well (within 2%) to the results of analytical calculations and modeled results (Table 1), giving students confidence in the methods.

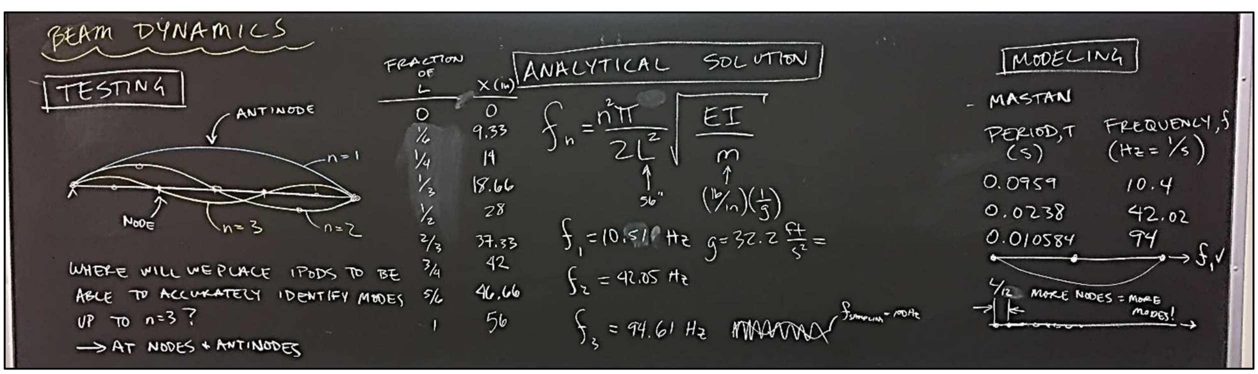

Figure 7. Board depicting testing protocol and results of the analytical solution and modeling groups.

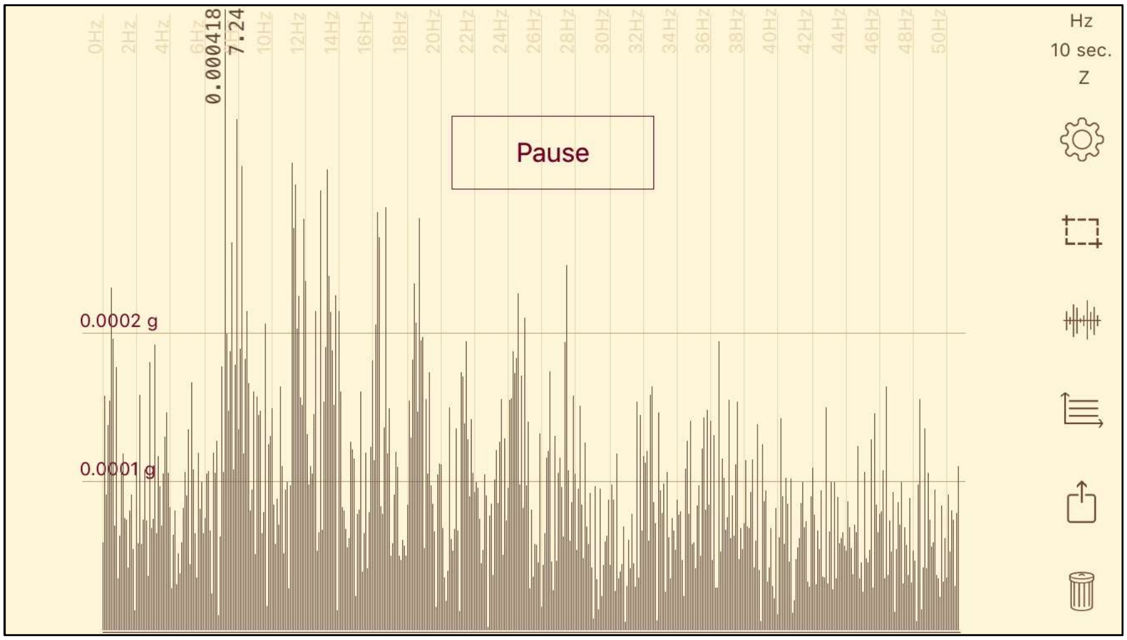

Figure 8. Vibration Analysis app displaying frequency spectrum with peak frequency (7.24 Hz) and amplitude (0.000418 g).

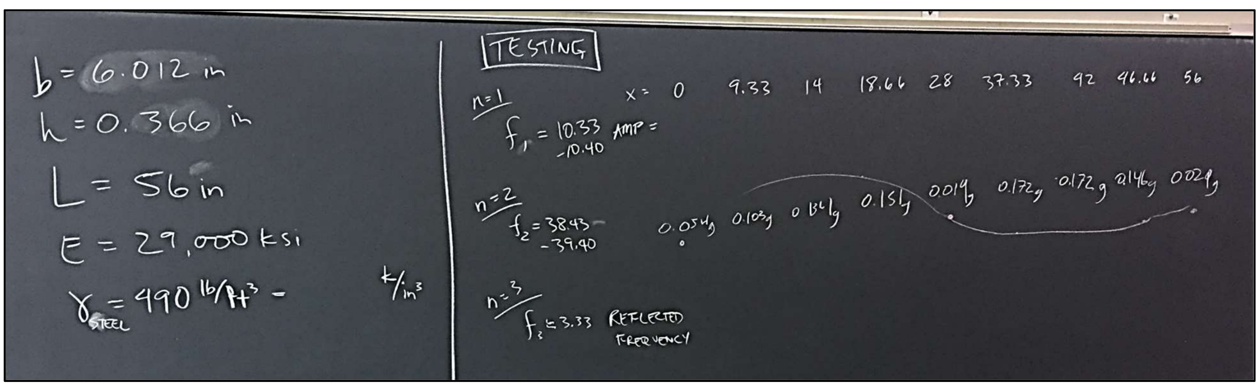

Figure 9. Board depicting beam parameters and results from the experimental testing group.

Analytical Calculation Group

Finally, the analytical calculation group struggled through various variable definitions and unit errors to arrive at results with which they were confident (see Figure 10), even as other teams were producing results to which they could compare. Surprisingly, it was this group that seemed most challenged by their task and required the most interaction with the instructor. This would fall into the category of a desirable difficulty, as this group was the best versed in the theoretical relationships involved in natural frequency and ultimately was able to explain reasons for the results of the other groups. The modal frequencies determined by each of the groups are provided in Table 1.

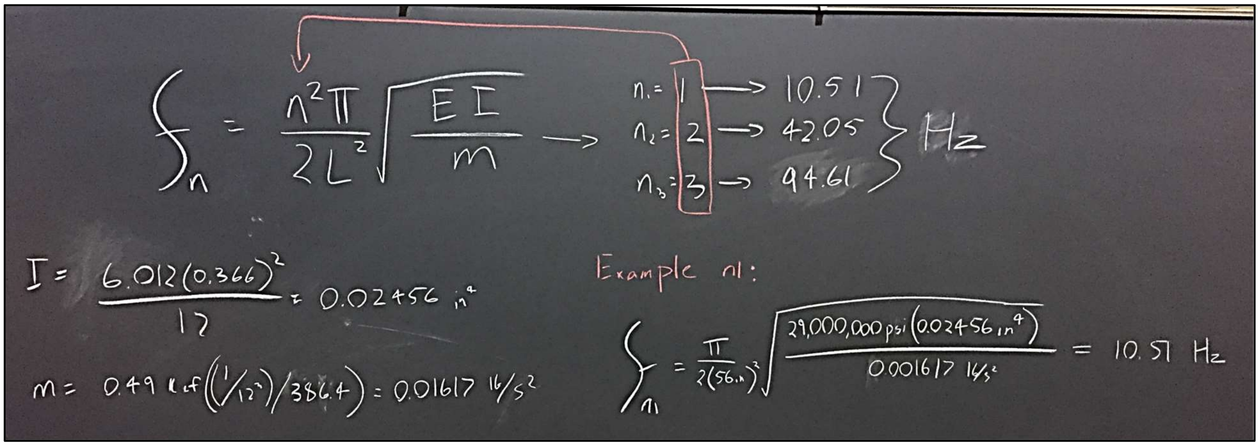

Figure 10. Board depicting details of calculations by the analytical calculation group.

Table 1. Modal frequencies (Hz) identified during the class activity by numerical modeling physical testing, and analytical calculation.

Mode	Numerical Modeling	Physical Testing	Analytical Calculation
1	10.50	10.33-10.40	10.51
2	42.02	38.43-39.40	42.05
3	94.48	3.33 (alias) → 96.67	94.61

The final discussion of these results was a powerful one, with each group describing to the others the challenges involved in their task. The conclusions of the class were valuable: that closed-form exact solutions are valuable when a problem has them, that numerical models are equally valuable and are more so when problems grow in complexity, and that the relationship between experimental testing and analytical solutions of any kind can be used to confirm lesser-known structural parameters or behavior. These conclusions formed the introduction to the topic and the basis for the pedestrian walkway field testing that was conducted during the laboratory activity.

Laboratory Activity

The laboratory activity consisted of periodic and harmonic forced vibration testing of a continuous pedestrian walkway bridge with 12-ft, 14.25-ft, and 22.10-ft spans in a campus building (Figure 11). The structure was first excited by periodic impact (jumping) at the centers of the center span and the long (west or right-most) span. The VibSensor app [14,15] was used to collect data for one minute and produce a frequency spectrum in which potential modal frequencies appear dominant (Figures 12 and 13). The VibSensor app differs from the Vibration Analysis app in that it prepares a more comprehensive report of the frequency spectrum with a longer window and identifies the two highest peaks rather than one. Where the Vibration Analysis app is valuable for its real-time frequency spectrum, VibSensor is valuable for its more complete report, triggering capabilities, and adjustable data collection window.

Figure 11. Pedestrian bridge with MC12x30 beams, looking west.

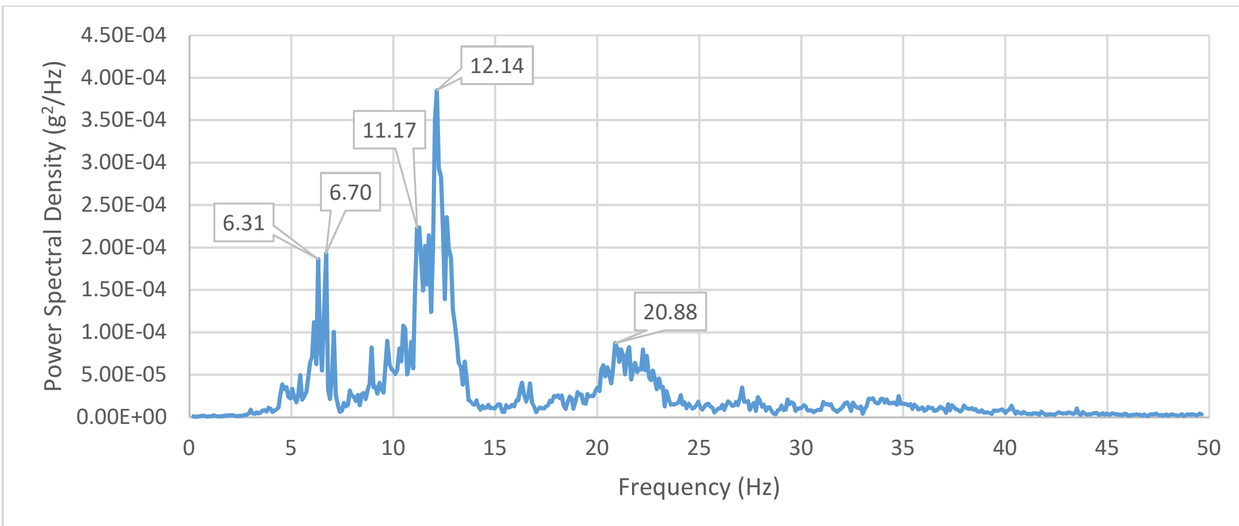

Figure 12. Frequency spectrum from impact and measurement at the center of the center span.

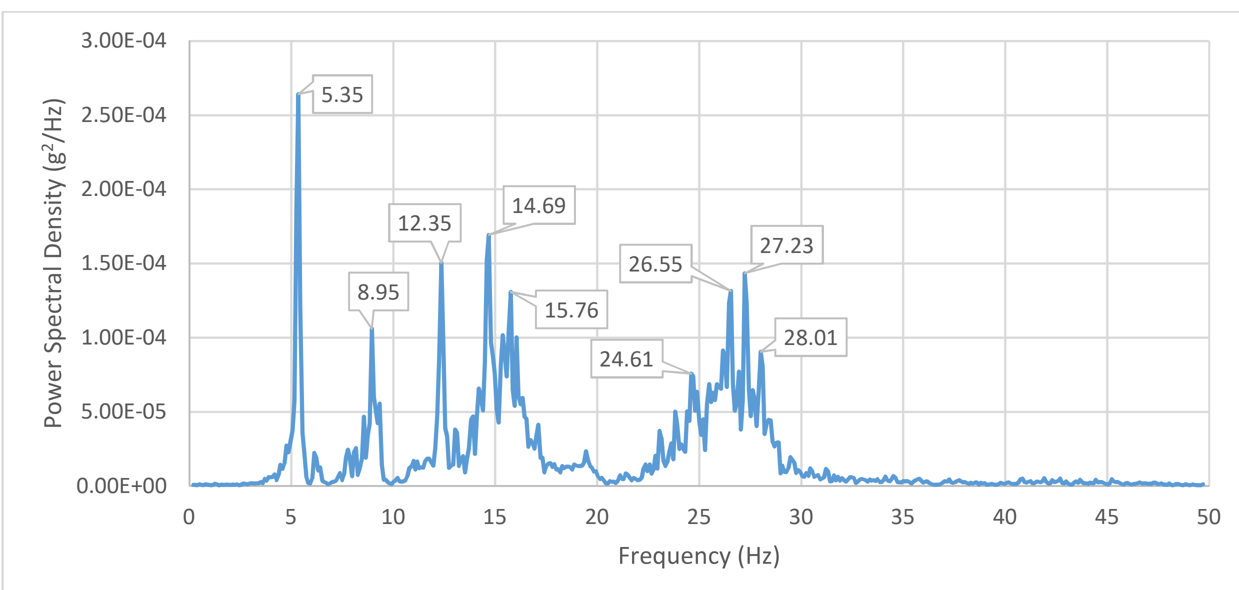

Figure 13. Frequency spectrum from impact and measurement at the center of the long span.

An APS 113 Electroseis™ long-stroke electrodynamic shaker with a 15-lb inertial weight, powered by an APS 125 amplifier, controlled with the APS VCS 401 Vibration Control System, and managed with Spektra vibration control software, was used to excite the structure with a known harmonic forcing. Similar systems are available from The Modal Shop and researchers have explored other less expensive means of producing excitations, for instance with low-frequency speakers or tactile transducers [16]. The shaker was deployed to the center of the two longest spans. Twelve iPods running the Vibration Analysis app were placed atop the MC12x30 beam at quarter points and supports of each span to measure response (Figure 14). The frequencies identified by periodic impact with the VibSensor app were used as initial forcing frequencies with adjustments made to the forcing frequency to identify maximum response. Students were impressed to observe resonance in a full-scale structure and quickly recognized many complicating factors involved in measuring accurate dynamic properties of a structure: a person's presence on the structure changed the distribution of mass of the system and had an influence on the amplitude of the response, the response of the structure was not purely vertical as railings oscillated laterally indicating more complex structural behavior than they had anticipated, and loose elements like the concrete deck panels vibrated independently from the structure in some cases. The ability of the students to experiment freely with the equipment led to valuable observations about structural modeling and natural frequency estimates.

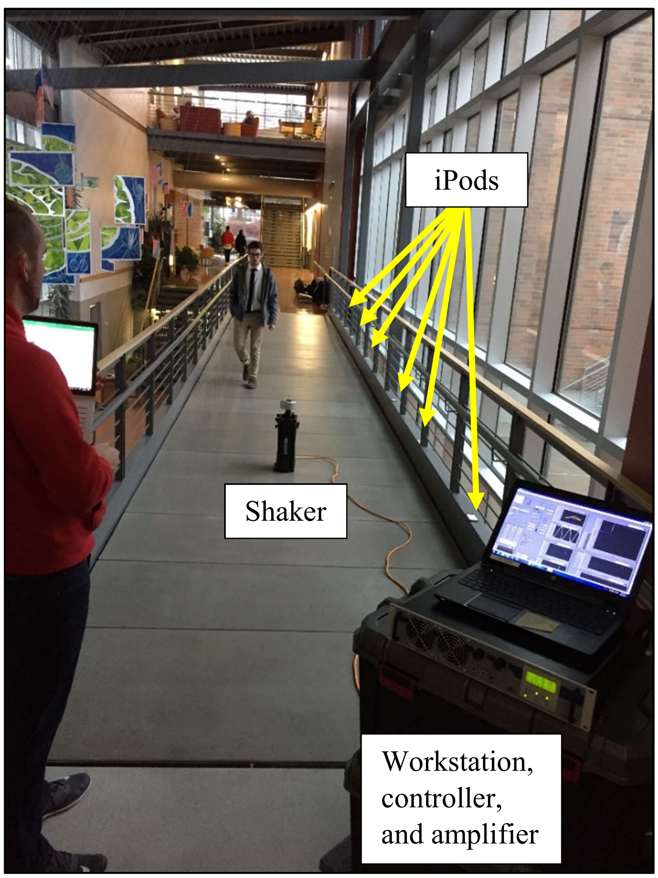

Figure 14. Harmonic forced vibration via APS 113 shaker on an interior 3-span pedestrian walkway; workstation off of structure, 12 iPods distributed along primary structural element.

The results of the harmonic testing can be seen in Figures 15 and 16. Interpreting these results requires some attention to the potential modes of the structure. Because the iPods produce the amplitude of vibration as an absolute value of RMS acceleration for a particular frequency, the phase of the vibrations cannot be discerned between iPods. Thus, a full-wave mode shape will be observed as a double-hump. The data could be adjusted manually to plot a structurally admissible mode shape. For instance, the mode associated with 9 Hz appears to have a node in the middle of the span, which is an indication of a full-wave mode shape in that span.

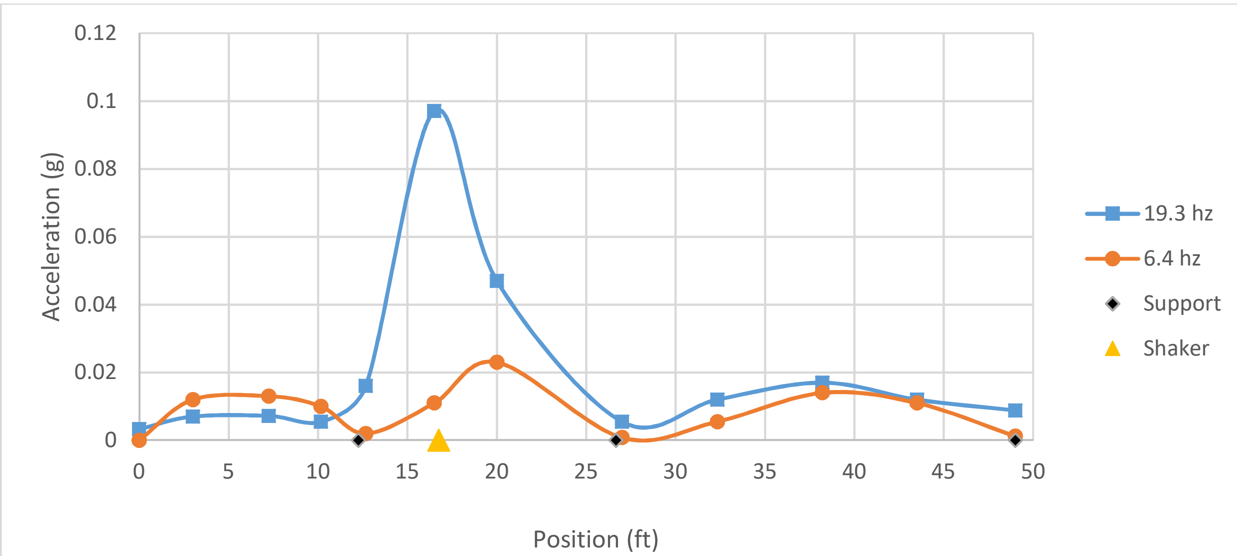

Figure 15. Response measurements with harmonic forcing of middle span.

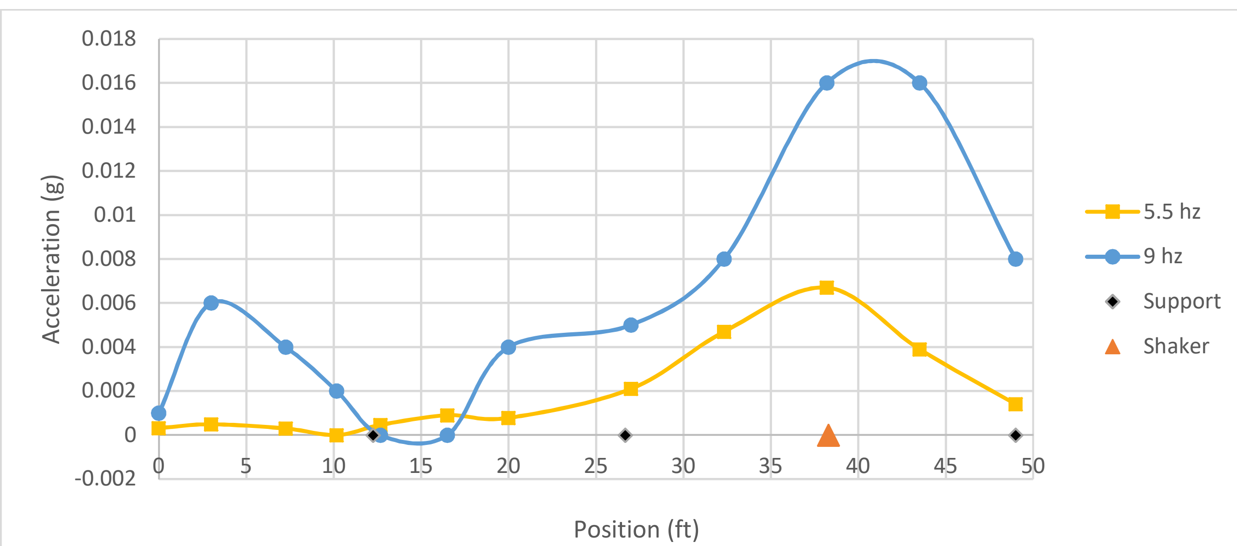

Figure 16. Response measurements with harmonic forcing of long span.

As a final step, students prepared a 1D model of the pedestrian walkway using MASTAN2 and attempted to modify the structural parameters (primarily support conditions and dead load estimates) to improve the relationship of the modeled and measured frequencies (Figure 17).

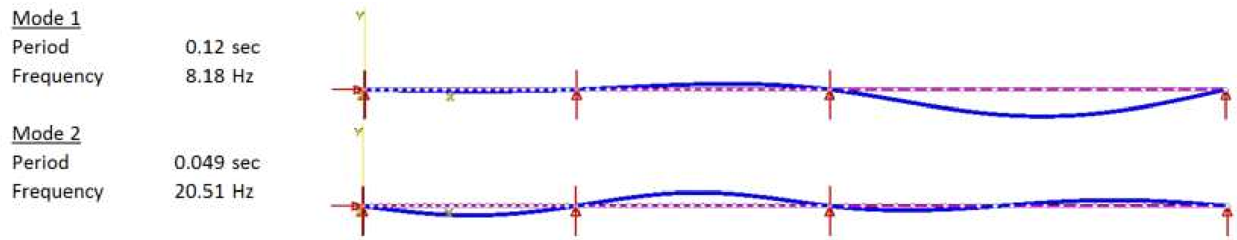

Figure 17. First-attempt results for the pedestrian walkway beam modelled in MASTAN2.

It was clear from the modeled results that the lowest observed frequencies during field testing were not reproducible without significantly softening the structural model. While the measured 9-Hz and 19.3-Hz frequencies were near the first two modal frequencies for the model (8.2 and 20.5 Hz), the resolution of the mode shapes from the field testing was not sufficient to confirm these modes. Adjustment of model parameters was left to the students to report in their laboratory memoranda. The students made various attempts to improve the results of their model by adjusting support conditions and dead load assumptions, a critical part of the model updating process for refined bridge load rating.

Assessment of Learning

Indirect and direct assessment of student learning was conducted to measure both student demonstration of knowledge and student perceptions of learning. Indirect assessment was conducted via online survey and was completed by seven of the students two weeks following the module activities and after they had submitted their laboratory report (Figure 19). Direct assessment was conducted using two artifacts: (1) a short-answer quiz based on the learning objectives and (2) a laboratory memorandum. The short-answer quiz was administered two weeks after the activity to assess each student's ability to demonstrate the module learning objectives (Figure 20). Laboratory report memoranda were gathered from the students in the week following the activities and evaluated by the instructor based on the module learning objectives. The results of these assessments will be described and discussed in more detail below.

Indirect Assessment: Student Self-Report of Ability to Demonstrate Learning Objectives

The students were asked to rate their ability to demonstrate the learning objectives on a 0 (low) to 100 (high) scale (see Figure 19 for results in rank order). Their responses indicate that they are most confident in the lower-cognitive-level learning objectives (define and explain). Their confidence drops as the learning objective increases in its cognitive level (use and apply). The students indicate better confidence in the structural dynamics concepts that were demonstrated in the module and are less confident in their ability to select appropriate structural analysis methods (1D, 2D, or 3D) and conduct model validation, which were prerequisite skills that were not taught directly in the module.

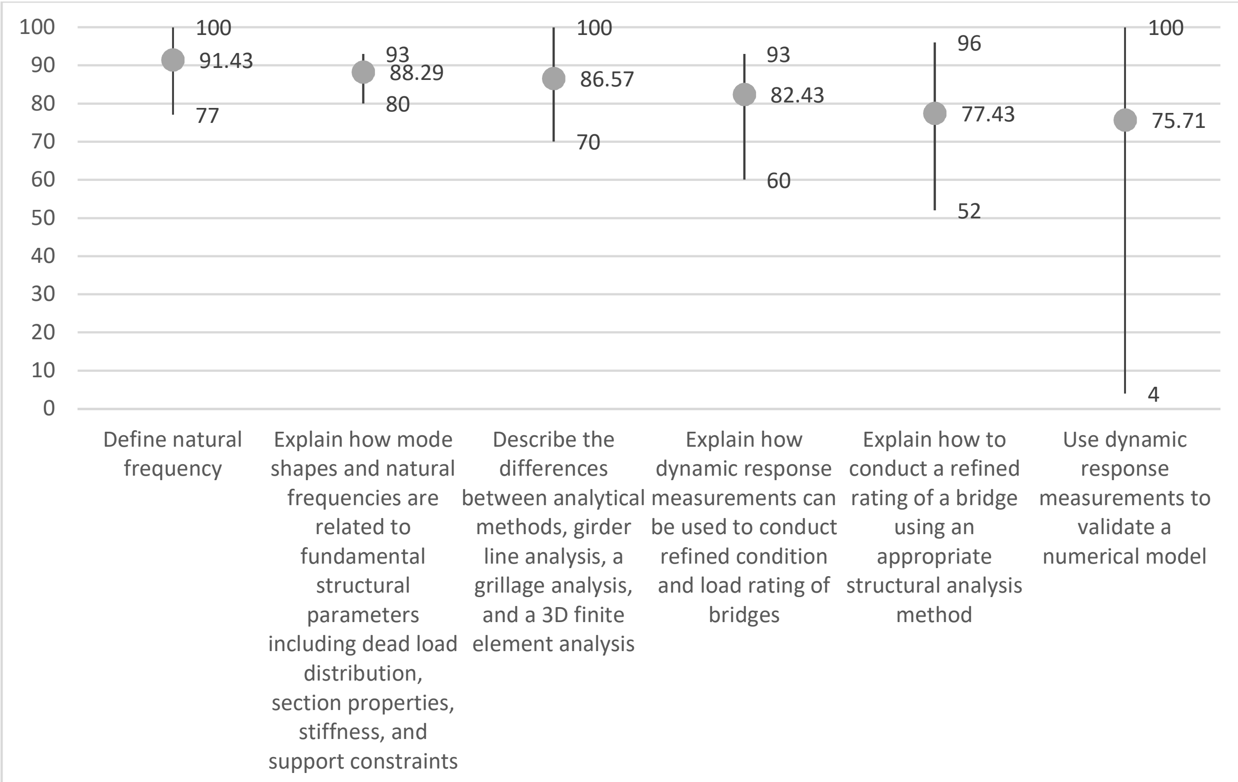

Figure 19. Student ratings (min, avg, max) of their self-reported ability to demonstrate learning objectives.

Direct Assessment of Students' Ability to Demonstrate Learning Objectives

A short-answer quiz, with the module learning objectives posed as questions, was given to the students two weeks after the activity. The quiz was scored on a four-point scale with scores of 3 and 4 indicating complete and correct responses demonstrating medium and high proficiency, and 1 and 2 indicating incomplete or incorrect responses demonstrating a relative lack of proficiency. The average of these scores was converted to a percentage and is provided for each quiz question in Figure 20.

In their short-answer quiz responses, students generally were capable of defining natural frequency by articulating resonance and free vibration concepts, earning them a 3 or 4. While they expressed an understanding of the influence of structural parameters on frequencies and mode shapes, they generally failed to clearly describe the impact of every parameter on natural frequency (for example whether a more restrained structure would have a higher or lower frequency), thus 5 of the 7 students earned a 2 on the second question. They identified the differences between various methods of structural analysis (1D, 2D, and 3D), but failed to connect these to their responses regarding refined methods of load rating. In this question, they tended to describe the bridge load rating process in general, not the refinement of the structural analysis model that would allow them to take advantage of measured dynamic response data. And while they were quite good at explaining how dynamic response data could be used to validate a numerical model, generally by achieving similar modal frequencies and shapes in the model and in reality, they expressed the least confidence in their ability to actually do this. This was likely the result of insufficient time spent adjusting structural parameters within the model to determine their influence. Also, model updating algorithms were not discussed in any detail. This elaboration could be added to the module in future offerings of the course.

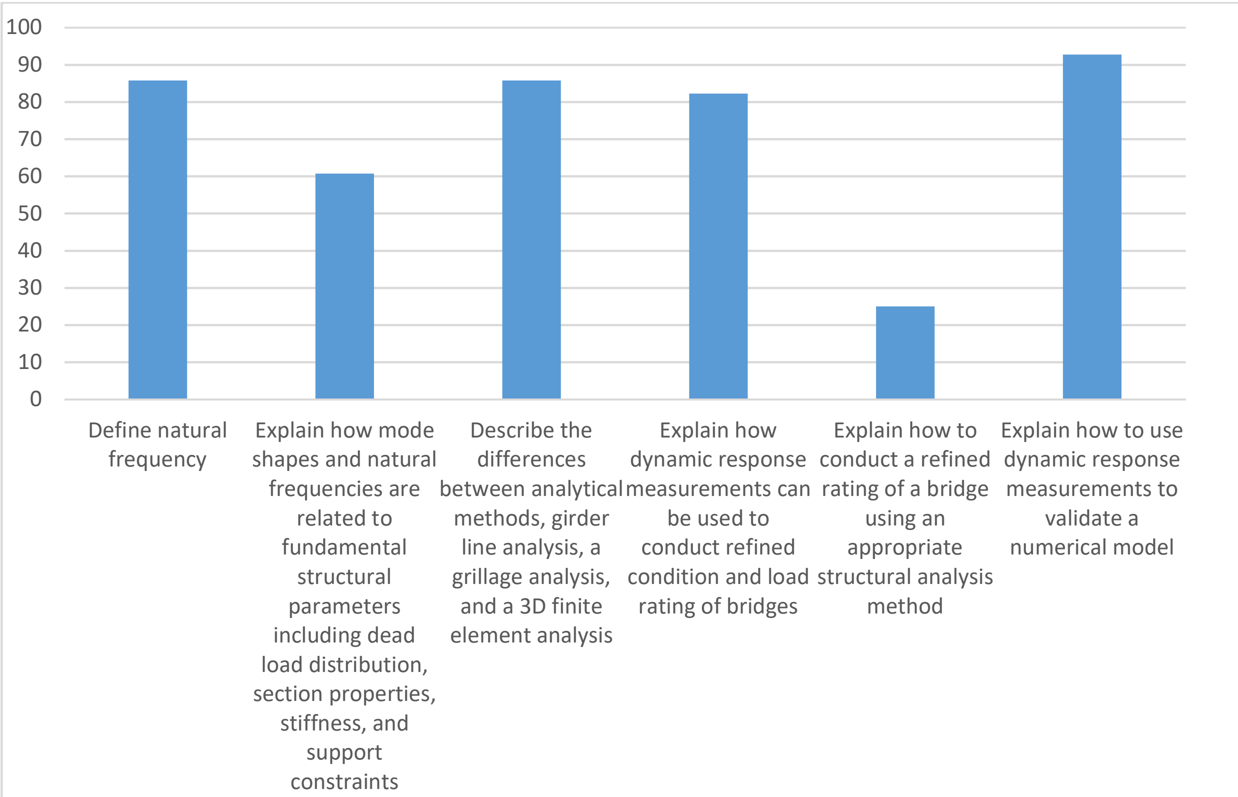

Figure 20. Average student scores (n=7) for each short-answer quiz question requesting demonstration of knowledge.

A comparison of student perception versus their ability as demonstrated in a laboratory report memorandum is very enlightening (Figures 19 vs 20). In general, students expressed relatively high confidence in their ability while their responses demonstrated a wider range of ability, a not uncommon result that may be described in part by the Dunning-Kruger effect, a cognitive bias of individuals with low ability to overestimate their cognitive ability [17]. However, in some cases the student responses were quite nuanced and demonstrated the value of the laboratory module in reaching beyond a purely board-based, textbook-based, or even a laboratory-based model and into the messiness of full-scale testing in the field.

Laboratory Report Memoranda Evaluation

Eight students submitted a laboratory report memorandum. Each memorandum documented the procedure and results of field testing and provided a discussion of the results as requested in the module handout (Figure 1). Evaluating these reports on the basis of the learning objectives provided the following insights:

1) Students used the concepts of natural frequency and mode shape accurately throughout their reports with only three students describing natural frequency in a way that amounts to a definition.
2) All students described clearly at least one of the structural parameters that could affect natural frequency, while five students described the impact of all parameters on the results (load, stiffness, connectivity, and load distribution).
3) Only two of the students discussed more complex models (grillage and 3D modeling) as a potential way to address differences in the experimental and modeled results.
4) Only three of the students connected the experiment to load rating of highway bridges.
5) All of the students discussed how to use dynamic measurements to improve a structural model, with six of the eight discussing this meaningfully.

The discussions in the reports demonstrated the challenge of using field testing to draw strong conclusions. Rather, the field experience made clear the limitations of structural modeling and the value of field measurement for decision making. For students, this experience is more often had when they practice engineering or study at the graduate level. More detailed prompts could be used in the future to illicit more detailed explanations from the students and encourage them to make a greater effort to explain differences.

Assessment of the Module

The final assessment that was conducted was an assessment of the module activities by the students. They were asked to rate the learning activities in the module according to the importance in support of their learning on a 100-point scale. The results of this survey are provided in rank order of the average in Figure 21.

Students ranked the field experience and the discussions following it as the most valuable aspects of the module, while testing of the prismatic beam and the value of iPods for data collection were ranked lower. None of the activities were deemed unnecessary and student comments corroborated these scores. When asked about the single most valuable aspect of the lesson, the student responses were:

- “I really found going to the Dow center and actually shaking the bridge very valuable. If we could have isolated the natural frequencies a little better, I think it could have been even better.”
- “Shaking the Dow Center bridge”
- “The actual discussion after the lab took place. This really allowed me to nail down what the results were showing.”
- “Seeing the difficulties associated with accurately modeling complex structures.”
- “I think the most valuable aspect of this lesson was actually seeing the methods be used in the 'field'.”
- “Dow Bridge analysis with the shaker and iPod tools.”

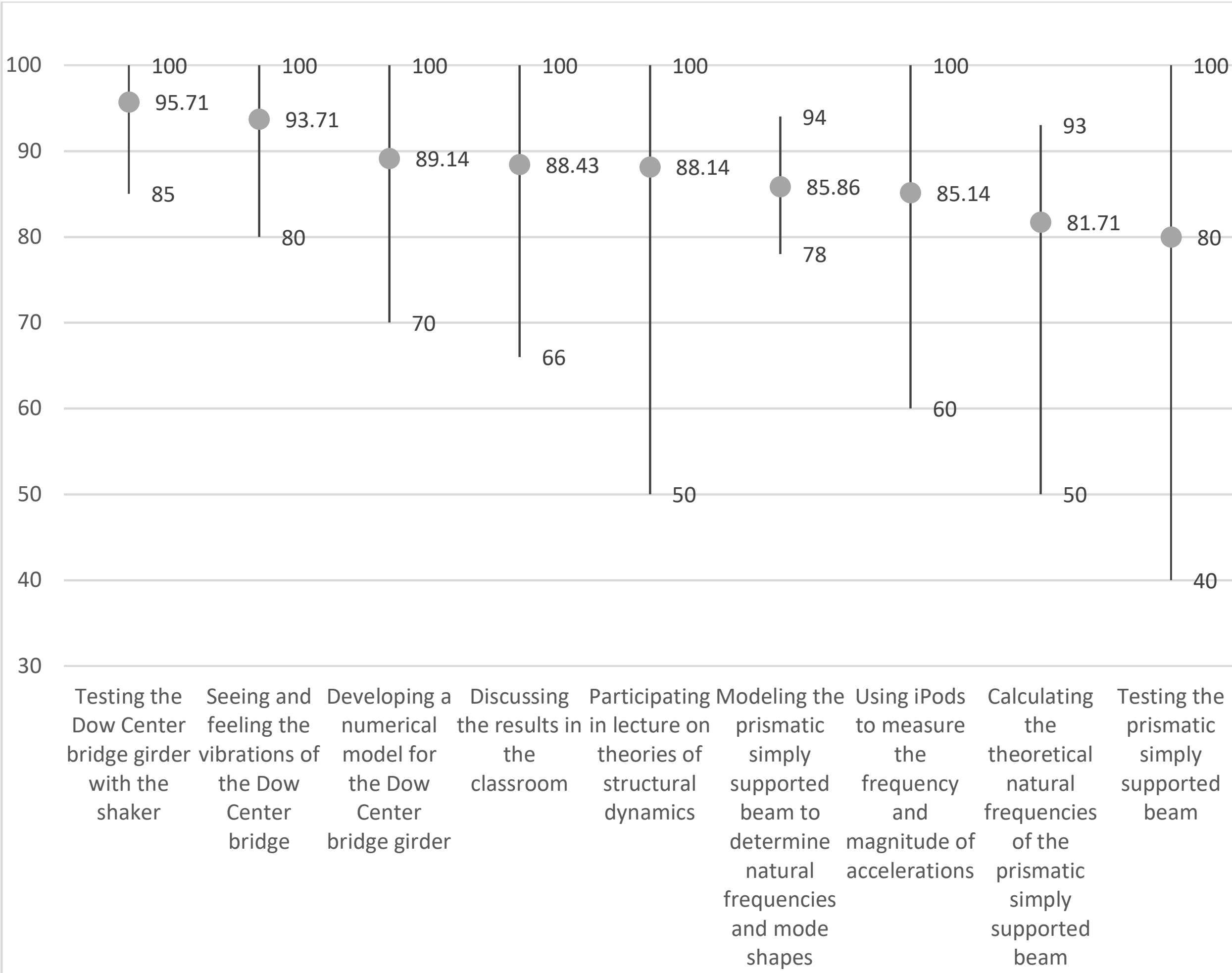

Figure 21. Student rankings (min, avg, max) of importance of the class activities in promoting their ability to demonstrate the learning objectives ordered by average (n=7).

The module was clearly a success based on student perceptions. They valued the opportunity to test at full scale and engage a problem that did not have a clear answer. However, they also struggled with explaining the complexity in structural mechanics terms and taking steps to model that complexity. This may say more about their preparation in experimentation than anything else. If this sort of experimentation were conducted more regularly in the curriculum, students might have a stronger foundation to work from. Similarly, if structural modeling were emphasized earlier and more often in the curriculum, the students might more readily embrace opportunities to model complexity.

Alternative Methods of Instruction

This module was developed in part to bring the results of funded research into the classroom but also in an attempt to quickly and effectively introduce students to a complex graduate-level topic. Reviewing the literature for other means of teaching this material identified nothing specific to modal analysis of bridges. However, modal analysis more generally, and more often applied to aerospace structures, has been written about extensively. Good papers exist that describe the value of laboratory experimentation generally and the importance of using learning objectives in this environment (e.g. [18]) but relatively little is available that indicates the value of field experiences as compared to bench-scale lab experiences. The papers by Cole McDaniel, Graham Archer, and others at Cal Poly are the best source for this as they focus on students developing a holistic sense of dynamic structural behavior [2,3,22]. ASEE's PEER database lists numerous papers related to modal analysis computational tools but rarely are the tools applied in a physical, not to mention field, environment. Most related to this work, Mahoney and Nathan [19] developed a demonstration-scale beam with an equation/model/test approach similar to that described here. They measured the value of this in a classroom-based vibrations course that had previously based on simulation and theory, measuring statistically significant learning gains and noting that students anecdotally appreciated the hands-on nature of the module.

Conclusions

As others have certainly discovered, students derive great benefits and tend to be most enthusiastic about experiences they have in the field seeing behavior at the full-scale of the work they may end up doing [2,3,18,19]. Simple model problems are much less interesting to students, despite the fact that they have clear learning benefits and support the students at lower cognitive levels, prior to addressing more complex problems at higher cognitive levels. There is a question that results from this: would the students feel as positively about their learning through the physical testing of a complex system if they had not already explored a simpler problem? Would the difficulties encountered in the complex system be as acceptable to them without such a confidence-inspiring foundation in the material (here, the laboratory-based simply-supported beam)? Previous educational research would indicate the answer to these questions is no, but students do not regularly think about this unless prompted [20]. A more problem-based approach may be valuable here, that focuses on the field experience first and uses just-in-time teaching of more fundamental material to describe what is observed. This may be an approach to apply in a future offering of this module.

The use of widely available mobile devices to measure dynamic response was a valuable component of the laboratory and makes such modal testing possible on a relatively small budget. As education researchers continue to investigate mobile devices and other inexpensive technology, structural dynamics laboratories will continue to improve [21]. Student-owned mobile devices can contribute to powerful structural dynamics lessons and spur experimentation beyond the classroom. Investment in a shaker system, as Laursen, McDaniel, and Archer have suggested [22], is an important step in bringing structural dynamics to life for students. The module including the use of inexpensive mobile devices for data measurement and collection as well as the assessment results reported here offer further demonstration of this potential.

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