HANDS-ON ACTIVITIES TO INCREASE STUDENT ENGAGEMENT IN UNDERGRADUATE STRUCTURAL DYNAMICS COURSE

BY

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SENIOR PROJECT REPORT

Submitted in partial fulfilment of the requirements
for the degree of Bachelor of Science in Architectural Engineering
at California Polytechnic State University – San Luis Obispo, 2018.

San Luis Obispo, California

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Abstract

This report documents the design and implementation of several physical models and hands-on lab activities incorporated in an undergraduate structural dynamics lecture and laboratory course pairing offered at California Polytechnic State University, San Luis Obispo in the Architectural Engineering department during the Winter 2018 quarter. In previous quarters, the laboratory course has lacked opportunities for students to conduct their own physical experiments and has consisted primarily of MATLAB programming activities. Efforts to illustrate the dynamic behavior of various structures have primarily involved instructor demonstrations or online videos.

The addition of physical models in the Winter 2018 offering promotes an engaging learning environment where students:

- Learn to collect acceleration data for free or forced vibration tests using an accelerometer application on a smartphone and generate plots of this data using MATLAB
- Conduct free vibration tests on various single-degree of freedom (SDOF) systems to investigate how mass, stiffness/height, material type, and damping type (pendulum or sloshing damper) effect structural period and damping
- Observe and analyze data from forced vibration tests using a small-scale shake table or eccentric mass shaker for various SDOF systems, diaphragms, and multi-story frames to understand natural frequency, dynamic amplification, and mode shapes
- Carry out a parametric study using a MATLAB tool that animates modal and time history response of a rigid diaphragm to investigate impacts of mass, geometry, and stiffness of this system type

Student feedback was collected via a survey at the end of the Winter 2018 quarter, and the responses were largely positive. In general, these results indicate that observing the dynamic response of physical structural models, collecting and processing data, and comparing the results to theoretical predictions is highly immersive and encourages students to develop their engineering intuition, rather than memorize equations or procedures.

The overarching aim of this report is to provide engineering educators at other institutions with a guide document on potential new curricula they could incorporate to achieve a balance of technical rigor and engaging activities in an undergraduate structural dynamics course. Detailed laboratory assignment handouts, sample data analysis (calculations and plots), as well as model fabrication drawings are included. Additional materials, such as sample MATLAB code and data files can be requested via email from the research team.

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1. Introduction

This document summarizes a collection of prototype teaching models developed by the authors to enhance the curriculum of two undergraduate courses offered during the Winter 2018 (W18) quarter in the Architectural Engineering (ARCE) department at California Polytechnic State University - San Luis Obispo (Cal Poly): ARCE 412, Dynamics of Framed Structures, and accompanying lab, ARCE 354, Numerical Analysis Laboratory. Cal Poly is known for its robust architectural engineering curriculum, and these courses cover advanced material not common in most other universities' undergraduate programs, including analysis of single- and multi-degree of freedom structures subjected to dynamic loads. Historically, these courses have had few interactive lab exercises. Keeping in mind Cal Poly's trademark "Learn By Doing" philosophy, the authors tried to develop engaging, hands-on activities that could be integrated into the curriculum to make difficult concepts more intuitive for students. The models are intended to be accessible in terms of cost and implementation so that instructors at other institutions can recreate them for their own use.

This document first identifies the topic area and specific learning objectives for each model or activity, then discusses the design process, including photographs and fabrication drawings of the final design. Descriptions of the implementation of each model or activity are provided along with sample data analysis. Materials lists with costs and potential suppliers are also included. Further lab instruction materials and construction details are available in the appendices. Student feedback is presented and discussed after all the models are described. This data was collected through surveys conducted at the end of the W18 quarter through a Cal Poly IRB approved study titled: *Use of Physical Experiments and Models in an Undergraduate Structural Dynamics Course (Project # 2018-075-CP)*, a collaborative effort between the student author and faculty member Dr. Anahid Behrouzi.

2. Institutional Context and Details of Course

Cal Poly is a predominantly undergraduate public university where the ARCE department is housed in the College of Architecture & Environmental Design (CAED) and has a total student enrollment of around 300 students. As a result of this polytechnic multi-disciplinary setting, the ARCE curriculum has been developed to provide students with exposure to underlying theory of structural behavior as well as practical hands-on design using common building codes. This learning occurs under the guidance of research and practitioner tenure-track/lecturer faculty. The Cal Poly ARCE department aims to prepare bachelor's degree students to enter directly into the structural engineering industry and take on challenges specifically related to seismic analysis and design. A strong understanding of structural dynamics forms the necessary basis for this type of earthquake engineering.

The structural dynamics lecture and lab combination discussed in this report, ARCE 412/354, is typically taken by junior architectural engineering students. The lecture can enroll up to 32 students and the corresponding lab is taught in two sections of up to 16 students. The courses are commonly offered in the Winter and Spring quarters, and have enrollment demands sufficient for two lectures and 3-4 lab sections. Lecture is taught in a standard classroom with a projector, instructor station (computer + laptop connection), white/blackboards, a large table at the front of the classroom to display models or demonstrations, and individual or shared student tables. Lab is taught in a computer laboratory with a MATLAB-enabled computer for each student and includes visits to the seismic lab with access to a small shake table, but no student workspaces.

The curriculum covers structural dynamics concepts that are not commonly taught in undergraduate programs and is based on the graduate structural dynamics textbook *Dynamics of Structures*, *5th Ed* by Anil K. Chopra (Chopra 2016). Students learn how to analyze single- and multi-degree of freedom structures for dynamic response by determining mass and stiffness matrices, calculating natural frequencies and mode shapes, and implementing modal analysis to determine the response histories for given forcing functions. Relevant portions of the syllabi for the W18 quarter are included in Appendix A. Historically, the course has also included numerical analysis concepts that are not as closely related to dynamic structural analysis, including Gaussian Elimination and LU decomposition. The ABET requirements have recently changed with regards to these mathematical topics, allowing some of the topics to be covered in less detail or removed from the course and replaced with more engaging lab activities that focus on the core structural dynamics concepts.

3. Proposed Physical Models and Lab Activities

3.1 Physical Model Type

The proposed physical models can be classified as table-top classroom models. The models are designed to be lightweight and transportable to facilitate their use in a variety of settings, namely lectures, labs, and office hours. Materials have been selected to be affordable and readily available at hardware or art supply stores. The model design assumes availability of basic power tools found in most workshops and the ability to use those tools. Several of the physical models employed the use of a water jet cutter, however, a laser cutter would be equally effective for cutting the components. Implementation of several of the models requires that at least one student per lab team have access to a functioning smartphone capable of downloading and utilizing basic applications.

3.2 Free Vibration of a Single Degree-of-Freedom System

3.2.1 Student Learning Objectives

Students enter this course with an elementary understanding of stiffness, including how to determine the stiffness of a fixed-free column, which is all necessary prior knowledge for this single degree-of-freedom (SDOF) free vibration lab. This activity is designed to introduce students to some of the core concepts that are covered throughout the course, including: natural frequency, damping, and parameters that affect the dynamic response of a structure. Additionally, students were introduced to a free smartphone accelerometer application ("Accelerometer" by DreamArc for iOS), which is used for several other lab activities throughout the W18 quarter.

3.2.2 Physical Model

The model is designed to be a SDOF cantilever model. The individual components of the physical model (base plate, cantilever members, and cell phone mount attachment) are shown in Figures 3.1(a-c); the experimental test set-up is shown in Figure 3.2. The figures shown here are those implemented in the Spring 2018 (S18) quarter. Both the original, and any updated fabrication drawings for the model components are included in Appendix D.1.

(a) Base Plate *(b) Cantilever Members* *(c) Phone Mount*

Figure 3.1: Single Degree-of-Freedom System Model Components

The base plate shown in Figure 3.1(a) is fabricated from 3/4" thick steel using the water jet cutter and welded; the clearance between the two feet are intended to reduce the risk of finger pinching when moving the model. The base plate is designed to be heavy enough to prevent rocking without clamping the model to a table-top. The design implemented in the W18 quarter included three adjustable slots that can be tightened into place with wing nuts as shown in fabrication drawings shown in Figure D.1. The design was updated for the S18 quarter to address the need for better fixity of the members to the base plate as shown in Figure D.2. In the updated design, the adjustable slots were welded upright to the base, and threaded bolts were welded to extend from the slots. Cantilever specimens were tightened into place against the vertical steel components with a washer and wing nut to create a fixed connection at the base.

Cantilever members shown in Figure 3.1(b) were cut with the water jet cutter in a variety of materials, which were selected to have different properties (namely modulus of elasticity) and with cost in mind. Member widths and heights were selected to have noticeable oscillations during free vibration without buckling under its self-weight with the weight of the phone and mount. The members shown in Figure 3.1(b) as pictured from top to bottom were 1/16” thick steel, 1/4" plexiglass, and 1/4" thick wood at 12”, 18”, and 22” lengths. All members used in the W18 quarter are 1” wide and have a reduced width of 3/4” at the ends to fit in the base slot; there are also two holes on each end. A suggested update to the specimen design would be to have a single hole at each end of the cantilever and maintain a constant width along the height. The two designs are shown in fabrication drawings shown in Figure D.4.

As shown in Figure 3.1(c), an off-the-shelf phone mount was used with an origami-style folded 24-gauge steel sheet metal attachment, fabricated with the water jet cutter, to securely attach the phone mount to the cantilever member so the phone screen is perpendicular to the direction of motion. The mount implemented in the W18 quarter has two holes for wing nuts, but a revised design having a single hole with a bolt welded into place would only require a single wing nut for attachment, thus reducing setup time.

Figure 3.2: Cantilever Setup

3.2.3 Instruction Using Physical Model

This lab activity for the W18 quarter has two parts -- hand calculations and experimental testing as described in lab assignment included in Appendix B.1. Each student group tests 12”, 18”, and 22” cantilevers of a single material. The students are asked to calculate the stiffness, natural circular frequency, and period for a single material and length using dimensions and weights that they measure with a caliper, tape measure, and weighing scale. Students are instructed to have at least one group member download a smartphone accelerometer application. They are given a tutorial on how to obtain and use the phone application, which is included in Appendix B.2.

To collect the experimental data, students are instructed to tighten a test specimen into the slot in the base plate and affix the phone mount to the free end of the cantilever. The phone is placed into the mount, and the accelerometer application is activated to collect data while the model is stationary. A student displaces the free end of the cantilever member a set distance and releases it from rest. Once the oscillations have fully attenuated, the accelerometer is stopped, and the data is emailed to one of the students as a comma separated values (.csv) file.

Students follow instructions on the accelerometer application tutorial to import the acceleration data into MATLAB. They are instructed to plot the acceleration time history for each cantilever length of their assigned material type on a single plot and determine the period of oscillation from the plots, which they compare with the values determined from hand calculations. Students are instructed to share data between groups in order to make comparisons of dynamic response between a larger variety of cantilever specimen materials and lengths. In their submittal, they are asked to include comments on the differences in response based on member height and material, as well as to comment on potential sources of error between the hand calculated periods and the experimentally found periods.

3.2.4 Sample Data Analysis

In the lab assignment, which can be found in Appendix B.1, the students are asked to complete a table with hand calculated values for each specimen. The completed table will look similar to Table 3.1.

Table 3.1: Sample Hand Calculations for SDOF Free Vibration Lab

Material	Approx. Length (in)	Approx. E (ksi)	t (in)	b (in)	L (in)	I (in^4)	K (lb/in)	Specimen Weight (oz)	Total Weight (lb)	Total Mass ($lb\text{-}s^2/in$)	ω_n (rad/s)	f_n (Hz)	T_n (s)
Steel	12	29000	0.059	1.000	9.75	0.0000171	1.606	3.2	0.563	0.001456	33.220	5.29	0.189
	18	29000	0.059	1.000	15.75	0.0000171	0.381	4.8	0.613	0.001585	15.506	2.47	0.405
	22	29000	0.059	1.000	19.75	0.0000171	0.193	5.9	0.647	0.001674	10.745	1.71	0.585
Plexiglass	12	460	0.197	1.000	9.75	0.0006371	0.949	1.6	0.513	0.001326	26.743	4.26	0.235
	18	460	0.197	1.000	15.75	0.0006371	0.225	2.5	0.541	0.001399	12.682	2.02	0.495
	22	460	0.197	1.000	19.75	0.0006371	0.114	3	0.556	0.001440	8.904	1.42	0.706
Wood	12	1900	0.290	1.000	9.75	0.0020324	12.499	0.9	0.491	0.001270	99.216	15.79	0.063
	18	1900	0.290	1.000	15.75	0.0020324	2.965	1.3	0.503	0.001302	47.720	7.59	0.132
	22	1900	0.290	1.000	19.75	0.0020324	1.504	1.6	0.513	0.001326	33.672	5.36	0.187

Where: E = modulus of elasticity (ksi)
t = member thickness (in)
b = member width (in)
L = effective member height (in)
I = moment of inertia (in^4)
K = stiffness (lb/in)
ω_n = natural circular frequency (rad/s)
f_n = natural frequency (Hz)
T_n = natural period (s)

The acceleration time histories recorded with the smartphone accelerometer application can be opened with MATLAB. The time histories for each of the nine specimen are shown in Figure 3.3.

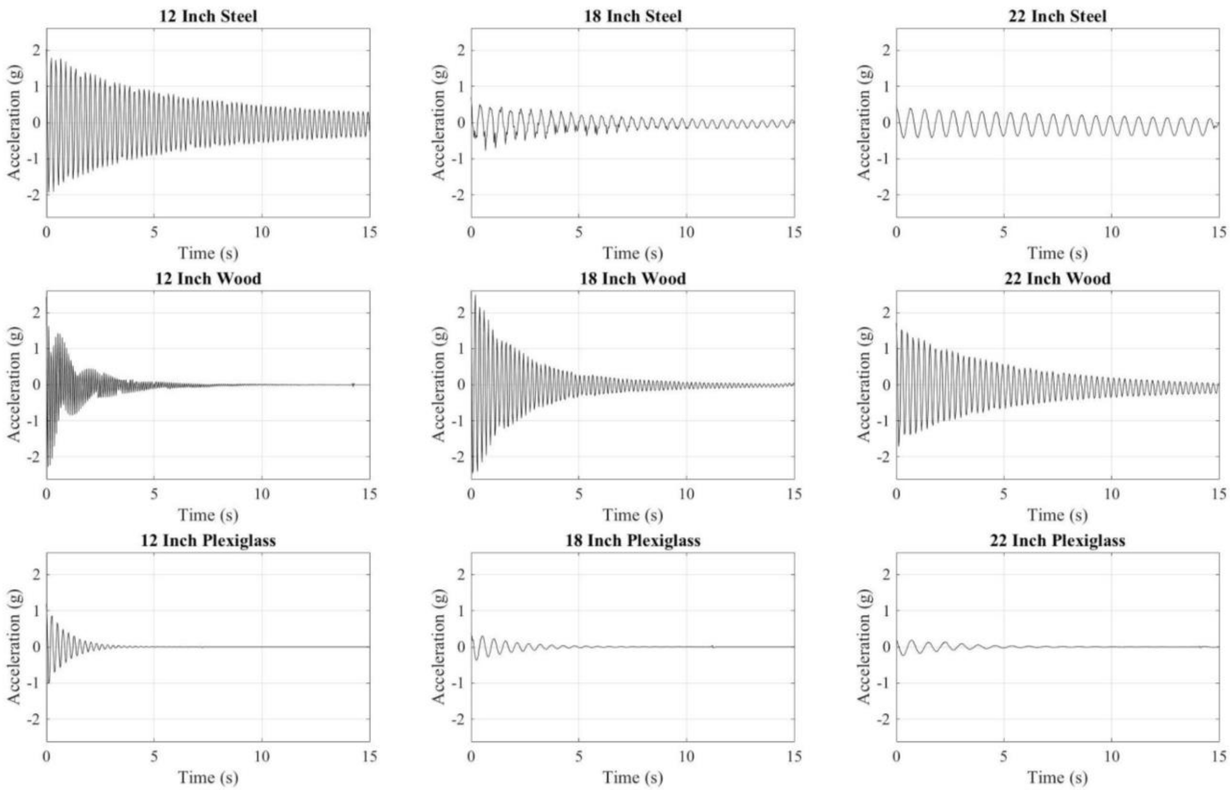


Figure 3.3: Acceleration Time Histories for Cantilever Specimens for SDOF Free Vibration Lab

While there are multiple ways to find the period with MATLAB code, for simplicity, students are asked to examine the peaks of the acceleration time history. Using the trace tool in the MATLAB plot, students find the time between two consecutive peaks. This is repeated for three sets of peaks, and the average is taken to be the period for that cantilever member.

Students are asked to comment on the results. They should note that taller members have longer periods and that the material affects the relative damping. They are also asked to comment on potential sources of error between the theoretical and experimental results. For example, all experimental results presented in this document have longer periods than those found with hand calculations. A reasonable explanation for this could be in the material property assumptions or the calculation of system stiffness is based on a length that may not be accurately measured to the actual center of mass. Additionally, in the lab students are instructed to assume that half of the member weight is lumped with that of the phone mount and smartphone; this lumped mass assumption may result in some inaccuracy as well.

3.2.5 Materials List

Students should be provided access to a tape measure, ruler, and weighing scale. Additionally, materials to fabricate the base plate, cantilever members, and cell phone mount attachment are listed in Table 3.2.

Table 3.2: SDOF Free Vibration Lab Materials List

Product Description	Dimensions	Supplier	Cost/Unit	# Units	Cost
3/4" Steel	12" x 12"	MetalsDepot	$59.77	1	$59.77
1/16" Steel	12" x 24"	MetalsDepot	$16.56	1	$16.56
1/16" Aluminum	12" x 24"	MetalsDepot	$23.00	1	$23.00
1/8" Wood	3" x 36"	Amazon	$9.38	1	$9.38
1/4" Plexiglass	12" x 24"	Amazon	$23.98	1	$23.98
24 Gauge Steel	12" x 24"	MetalsDepot	$9.00	1	$9.00
1/4" Dia. Bolts	-	Home Depot	$0.17	8	$1.36
1/4" Wing Nuts (4 pack)	-	Home Depot	$1.18	2	$2.36

Total Cost	$145.41

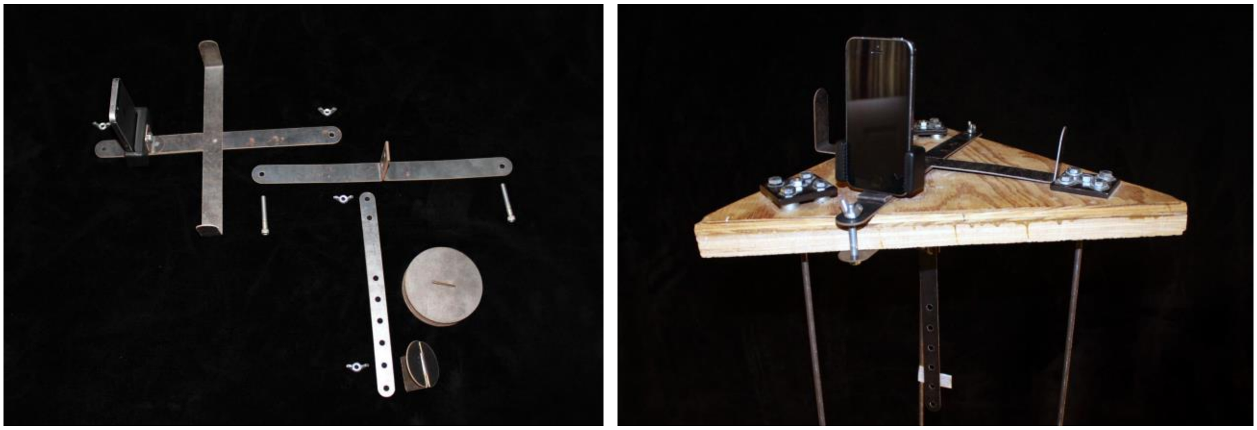
3.3 Structural Damping and the Logarithmic-Decrement Method

3.3.1 Student Learning Objectives

Students are introduced to damping, a concept pertinent in the seismic design of structures. In this activity, students experiment with a triangular model that can be equipped with a pendulum mass and a sloshing liquid damper so students can observe the effects of different damping mechanisms on free vibration response. Using the same smartphone accelerometer application from the activity from Section 3.2, students record acceleration time history data which they use to calculate the damping ratio using the logarithmic-decrement method as well as to determine the equation of motion for damped free vibration.

3.3.2 Physical Model

An existing triangular model was used for this activity; the dimensions, column fixities, material properties, and weight of this structure can be found in Figure D.14. In previous quarters, students have conducted free vibration tests to estimate: (i) the period of this structure by using a stopwatch to measure the time it takes to complete twenty cycles of motion, and (ii) the damping ratio by determining the number of cycles required for the displacement amplitude to decrease from 3” to 1”. The major update to the triangular model was an attachment for pendulum mass and sloshing liquid dampers to demonstrate the effects of different damping mechanisms. In creating this attachment, the original model was not to be permanently altered or damaged. The attachment is composed of the upper mount, lower mount, and slotted weights as illustrated in Figure 3.4 and described below. Fabrication drawings for the model components are included in Appendix D.2. *Note*: all steel components were cut using the water jet cutter.



(a) Damping Attachment Components *(b)Damping Attachment affixed to Triangular Model*

Figure 3.4: Triangular Structural Damping Model Components

The upper mount is designed to hold a plastic Tupperware® container in place, which can be filled with water to act as a sloshing liquid damper. There is a steel strap that spans across the top of the triangular wooden diaphragm with holes at each end to attach to the lower mount. Spot welded to this is a T-shaped piece of 1/16” steel. Each end of the T-shaped component has tabs bent at 90-degree angles to prevent sliding of the Tupperware® container; an additional tab has a hole for attaching the cell phone mount.

The lower mount is composed of a bent T-shaped steel strap with a length equal to the upper mount strap, and it is connected to the upper mount with a nut and bolt at each end. The vertical portion of the T-shaped strap, located at its mid-span, has two holes – one to act as the pivot for the pendulum and the other to lock the pendulum in place. The pendulum lever arm is a 1/16” metal strap with multiple holes for attaching weights at various heights.

Five circular slotted weights were cut from 1/8" steel and designed to slide onto the hanging pendulum or on one of the vertical tabs on the top mount (to compare the sloshing mass to an equivalent fixed mass). A seat for the weights is cut from 1/16” steel and folded to be attached to the pendulum lever arm with a wing nut. A recommended update to the seat is a design where it only touches one side of the pendulum arm allowing a bolt to be welded into the seat so that a single wing nut would be used to attach the weights, reducing setup time.

3.3.3 Instruction Using Physical Model

Student groups are instructed to set up and collect acceleration data for one of five different conditions shown in Figure 3.5: (a) locked pendulum with no weight attached, (b) locked pendulum with slotted weights fixed on the top of the structure, (c) locked pendulum with weights on pendulum, (d) unlocked pendulum with weights on pendulum, and (e) plastic Tupperware® container filled with water equivalent to weight of slotted weights (a measuring cup indicating the volume of water equivalent to one slotted weight is provided). Students are given a table of values that summarizes the weight of all the components in order to determine the mass for each of the five scenarios.

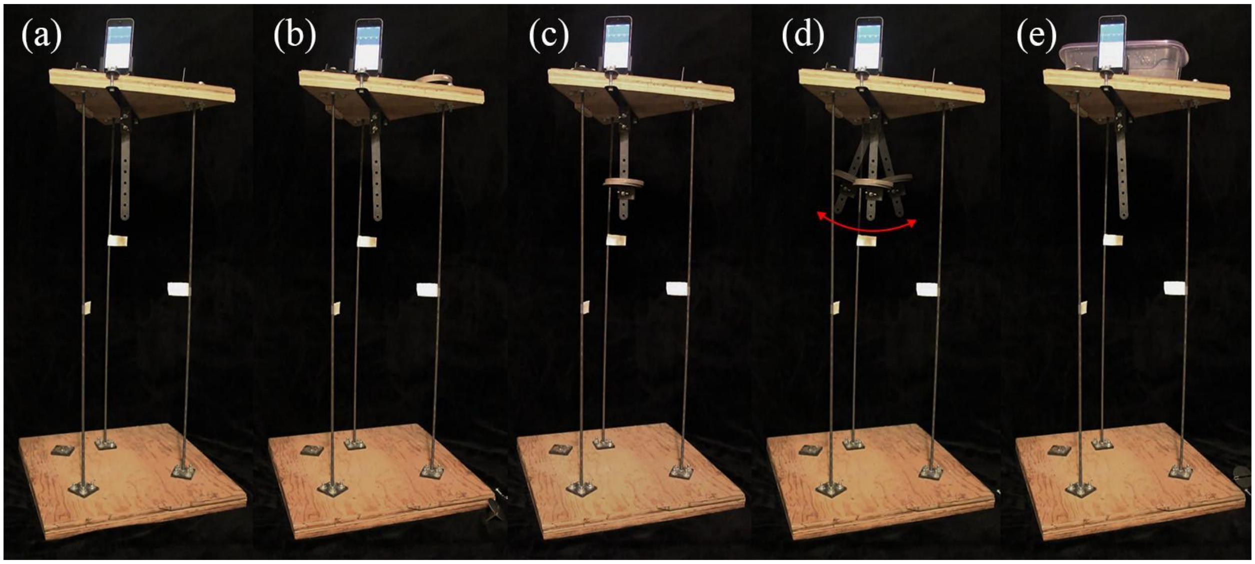


Figure 3.5: Damping Configurations (a-e)

For each condition, the triangular wooden diaphragm is displaced 2” and released into damped free vibration scenario. Once the data is recorded, students plot the acceleration time history in MATLAB utilizing the “spline” function to smooth the data. With the acceleration time history plots, students implement the logarithmic-decrement method to determine the damping ratio and associated damping coefficient for conditions (a -c); for the S18 lab this was updated to conditions (a-b). An example of this procedure is presented in the Section 3.3.4. Students use these values to determine the equation of motion for damped free vibration and to plot the idealized displacement time history. Lastly, students comment on the damping values they calculated as well as trends they observed in the damped scenarios.

3.3.4 Sample Data Analysis

To find the damping ratio and ultimately plot the idealized displacement time history for damped free vibration, students use the logarithmic-decrement method which is described in Chopra (2016) Chapter 2. First, the acceleration time history for each condition is plotted, as shown in Figure 3.6.

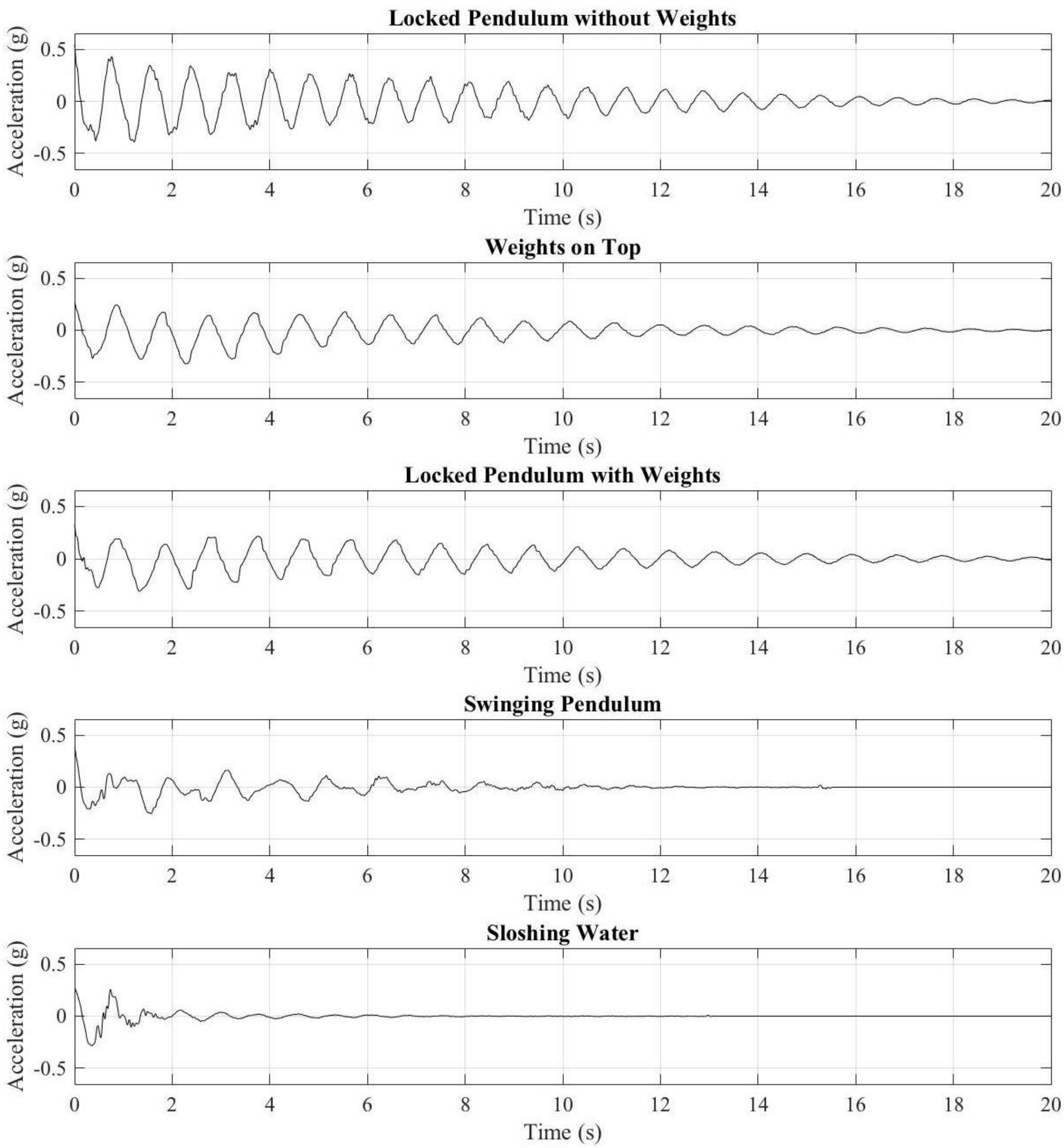


Figure 3.6: Acceleration Time Histories for Triangular Damping Model

Using the trace tool in the MATLAB plot, students determine the damped period and the acceleration values at several peaks. Equation 3.1 is used to find the damping ratio, ζ, based on the logarithmic-decrement method for when ζ is small (< 0.20). This method is only possible for conditions with a regular period and signal attenuation, and is not valid for the pendulum mass or sloshing water conditions.

$$\zeta = \frac{ln(\frac{\ddot{u}_i}{\ddot{u}_{i+j}})}{j2\pi} \qquad \text{[Equation 3.1]}$$

Where $\ddot{u}_i$ is the peak acceleration, and $\ddot{u}_{i+j}$ is the peak acceleration *j* cycles later.

The equation of motion for damped free vibration can be expressed as shown in Equation 3.2:

$$m\ddot{u} + c\dot{u} + ku = 0 \qquad \text{[Equation 3.2]}$$

Where $\ddot{u}$ = acceleration
$\dot{u}$ = velocity
u = displacement
m = mass
c = coefficient of damping = $2\zeta m\omega_n$
k = stiffness

The right side of the equation is zero because there is no forcing function acting on the system during free vibration. Once the damping ratio is calculated, Equation 3.3 can be used to determine the idealized displacement time history, *u(t)*. This can be derived from the equation of motion using linear algebra, as described in Chopra (2016) in Chapter 2. The period found by examining the peaks of the acceleration time history is the damped natural period, which is used to find the damped natural circular frequency. Equation 3.4 is used to determine the undamped natural frequency.

$$u(t) = e^{-\zeta\omega_n t}(A\cos\omega_D t + B\sin\omega_D t) \qquad [\textit{Equation 3.3}]$$

$$A = u_0 \qquad [\textit{Equation 3.3a}]$$

$$B = \frac{\dot{u}_0 + \zeta\omega_n A}{\omega_D} \qquad [\textit{Equation 3.3b}]$$

$$\omega_D = \omega_n\sqrt{1-\zeta^2} \qquad [\textit{Equation 3.4}]$$

Where ω_D= damped natural circular frequency
ω_n= natural circular frequency
u_0= initial displacement
$\dot{u}_0$= initial velocity

Students are asked to plot this idealized displacement time history for conditions (a-c). An example of the idealized displacement time history is shown in Figure 3.7 for condition (a).

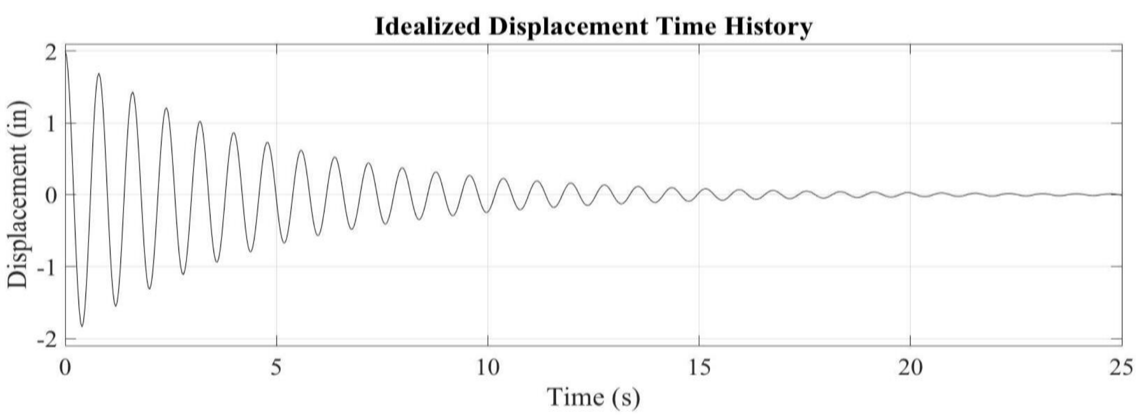


Figure 3.7: Idealized Displacement Time History for Triangular Damping Model Condition (a)

3.3.5 Materials List

Students should be provided access to a tape measure or ruler and weighing scale. Additionally, materials to fabricate the attachment for the existing triangular mount are listed in Table 3.3.

Table 3.3: Damping Attachment Materials List

Product Description	Dimensions	Supplier	Cost/Unit	# Units	Cost
1/16" Steel	12" x 24"	MetalsDepot	$16.56	1	$16.56
1/8" Steel	12" x 12"	MetalsDepot	$14.64	1	$14.64
Tupperware	12" x 24"	Dollar Tree	$1.00	1	$1.00
				Total Cost	$32.20

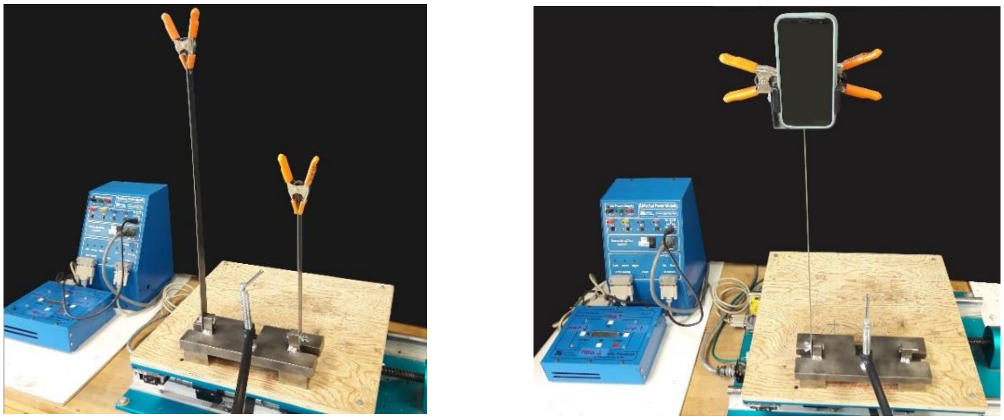
3.4 Harmonic Forced Vibration of a Single Degree-of-Freedom System

3.4.1 Student Learning Objectives

Having taken several structural analysis courses, students are familiar with calculating static deflections; this activity introduces them to the concept of dynamic amplification due to a harmonic force input. Students first observe a frequency sweep for two steel cantilever models on a Quanser Shake Table II. Students then use acceleration data collected during a frequency sweep of a cantilever models to experimentally determine natural frequency and damping ratio to develop a dynamic amplification (R_d) curve and calculate the R_d factor for any given forcing frequency. By multiplying a static deflection by the R_d factor for the forcing frequency of a harmonic input, the actual peak deflection can be determined.

3.4.2 Physical Model

Steel cantilever specimen(s) described in Section 3.2 are fixed to the base plate and clamped to the shake table. Figure 3.8(a) shows the two cantilever test set-up and Figure 3.8(b) shows the frequency sweep test set-up where acceleration time history data was collected for a single 22” steel cantilever specimen using the smartphone accelerometer application. Additional mass (clamps) were fixed to the cantilevers.



(a) Two Cantilever Set-up for Observation *(b) Cantilever Set-up for Data Collection*

Figure 3.8: Shake Table Set-ups for Student Observation (left) and Data Collection (right)

3.4.3 Instruction Using Physical Model

Prior to the Lab Session

The process of recording acceleration data for a complete frequency sweep is time intensive; therefore, it was not possible for students to record and analyze the data in a single three-hour lab session. To address this, the acceleration data was recorded by the authors beforehand, and the raw acceleration data was given to the students in a single Excel file. To perform the frequency sweep, first the natural frequency was found to be roughly 1.00 Hz. Once this was determined, 20- 30 seconds of acceleration data was collected for frequencies ranging from 0.50 Hz to 3.00 Hz. While conducting the frequency sweep, it is helpful to continually update a plot of peak accelerations versus frequency to verify the data and to address any errors that occur during data acquisition, particularly due to jolting of the model when starting or stopping the accelerometer application.

During the Lab Session

First, students observe frequency sweeps for 12” and 22” steel cantilevers. They are instructed to record qualitative observations and note the natural frequency for each (where they observed the largest deformation response). This allows students to make observations about resonance and dynamic amplification.

Then, students are given the pre-recorded acceleration data associated with each forcing frequency applied to the 22” steel specimen and instructed to import the data into MATLAB to plot the normalized peak acceleration versus frequency. As an additional activity, students are asked to create approximate R_d curves for a SDOF system with given weight, stiffness, and various damping ratios; based on the forcing frequency, they then use the curve to determine the appropriate R_d factor. The Excel file with the raw acceleration data and a MATLAB script that creates the R_d curve are available upon request.

3.4.4 Sample Data Analysis

Students use the raw acceleration data provided in a single Excel file to write MATLAB code to find the maximum acceleration for each of the forcing frequencies and create a plot of peak accelerations versus forcing frequency, as shown in Figure 3.9.

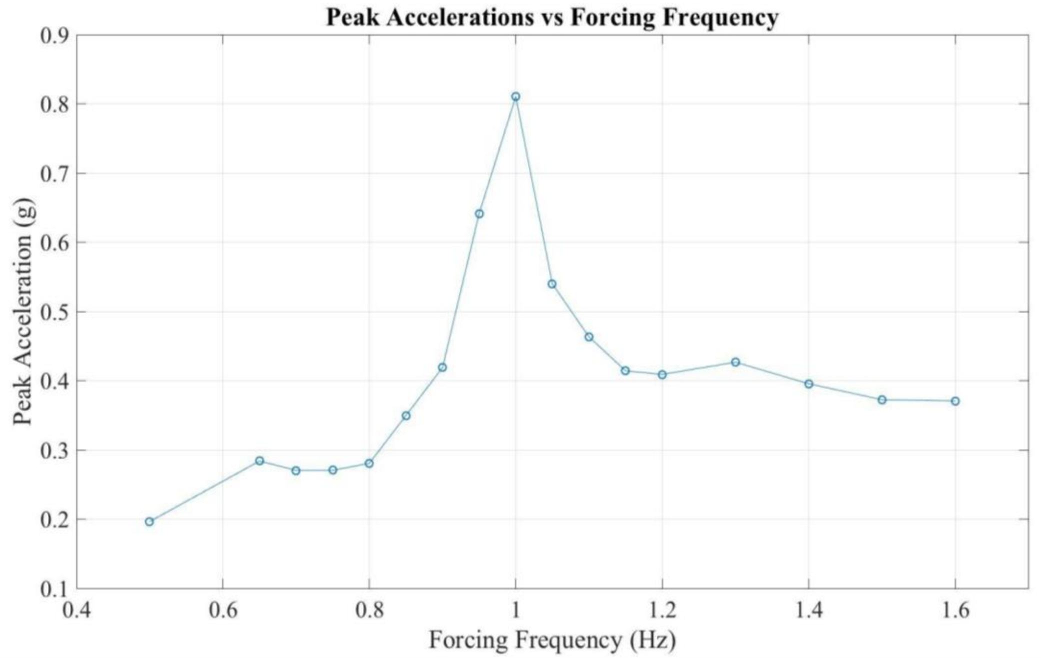


Figure 3.9: Peak Acceleration vs Forcing Frequency, Raw Data

The half-power bandwidth method described in Chopra (2016) Chapter 3 makes use of the expression shown in Equation 4.1 to find the peak acceleration values that corresponds to half power bandwidth, and the corresponding frequencies, f_1 and f_2, are found using MATLAB. Figure 3.10 shows the peak acceleration vs forcing frequency plot with the splined data and with the maximum peak (resonant amplitude) acceleration and half-power accelerations indicated.

$$A_{half-power} = \frac{A_{max}}{\sqrt{2}} \qquad \text{[Equation 4.1]}$$

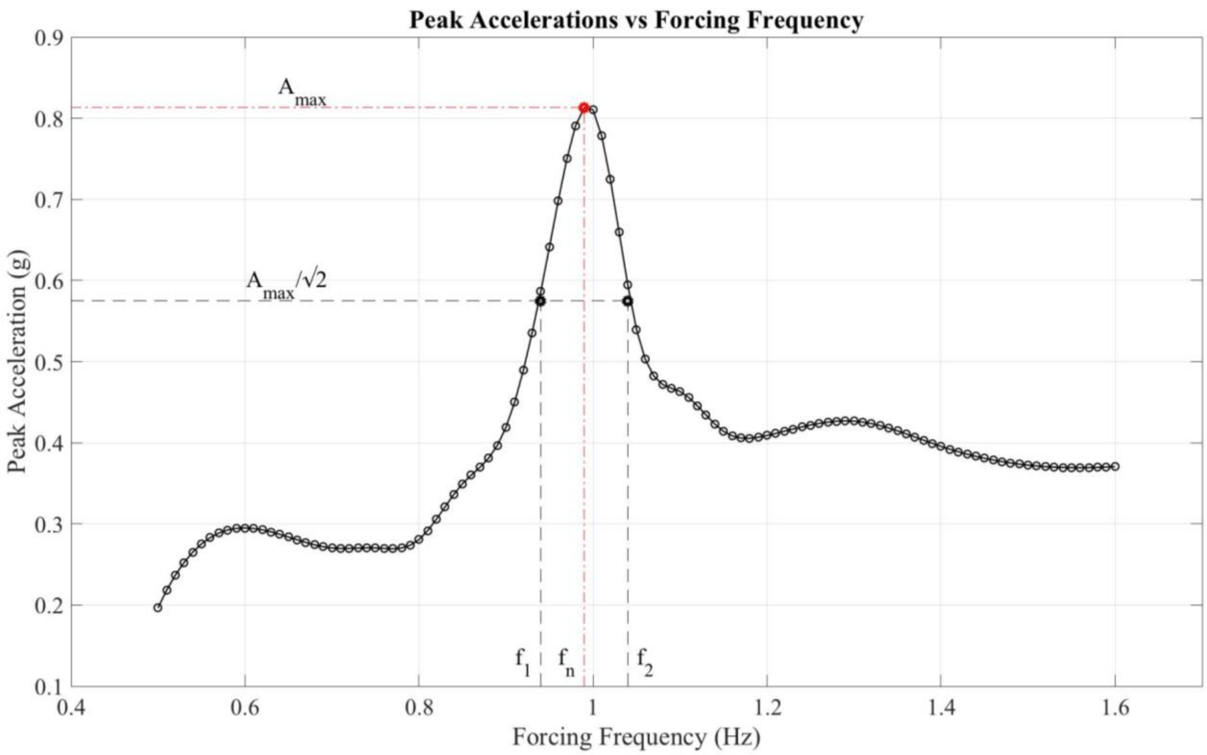


Figure 3.10: Splined Peak Acceleration vs Forcing Frequency Data with f_1, f_2, and f_n Indicated

The damping ratio (ζ) is found with Equation 4.2. With the damping ratio known, Equations 4.3 is used to determine the normalized forcing frequencies (β), and Equation 4.4 is used to determine the dynamic amplification factor (R_d), which can be plotted against the normalized frequencies to create the R_d curve, shown in Figure 3.11.

$$\zeta = \frac{f_2 - f_1}{2f_n} \quad \text{[Equation 4.2]}$$

$$\beta = \frac{\bar{f}}{f_n} \text{ where } \bar{f} \text{ is forcing frequency (Hz)} \quad \text{[Equation 4.3]}$$

$$R_d = \frac{1}{\sqrt{(1-\beta^2)+(2\zeta\beta)^2}} \quad \text{[Equation 4.4]}$$

In future quarters, students could be asked to write MATLAB code that plots the R_d vs. forcing frequency, like that shown in Figure 3.11 curve using the following steps:

1. Plot raw peak acceleration vs frequency,
2. Spline the data to generate a smoother curve with additional interpolated points,
3. Find the peak acceleration and associated frequency,
4. Use half-power bandwidth method to find the damping ratio,
5. Use a “for loop” in MATLAB to determine beta and R_d for each frequency, and
6. Plot the R_d curve.

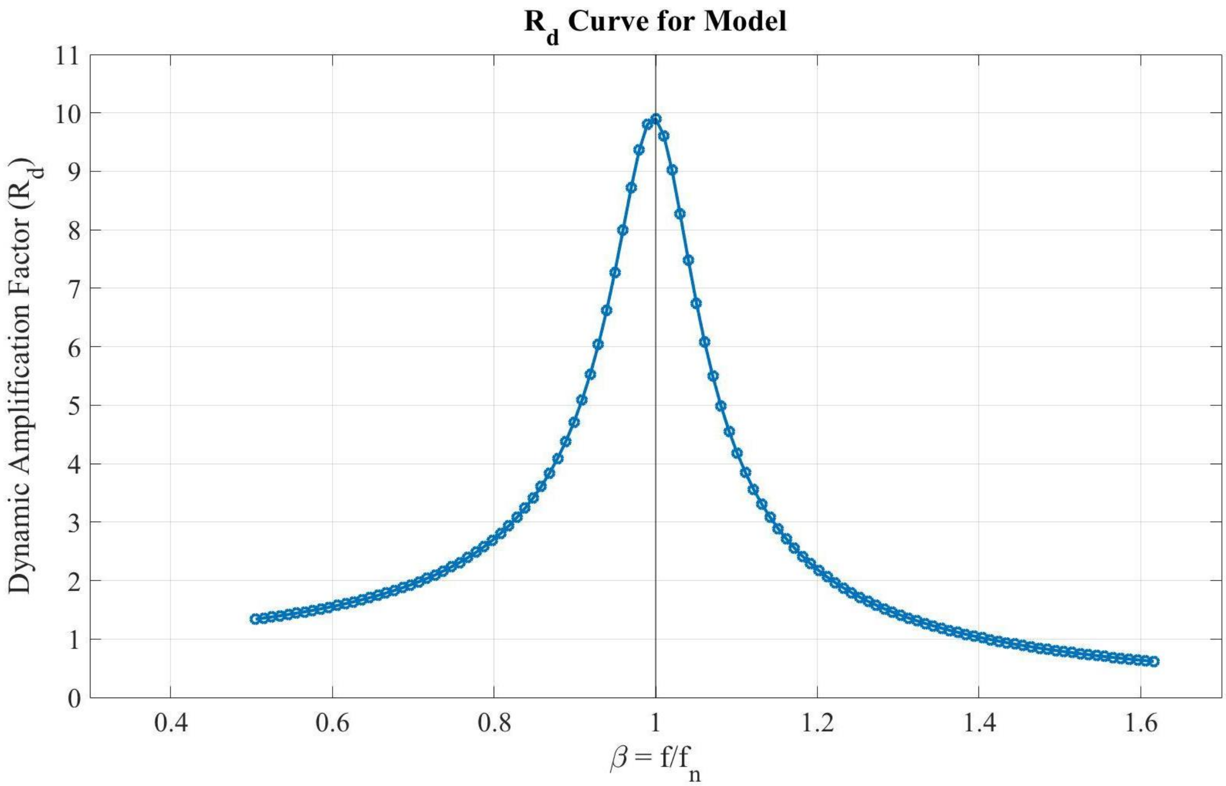


Figure 3.11: R_d Curve for the 22" Steel Cantilever with Clamp as Weight

3.4.5 Materials List

Refer to Section 3.2.5 for the materials and cost of this model. Pricing and other information regarding the shake table can be found at https://www.quanser.com/.

3.5 Multi Degrees of Freedom - Rigid Diaphragms

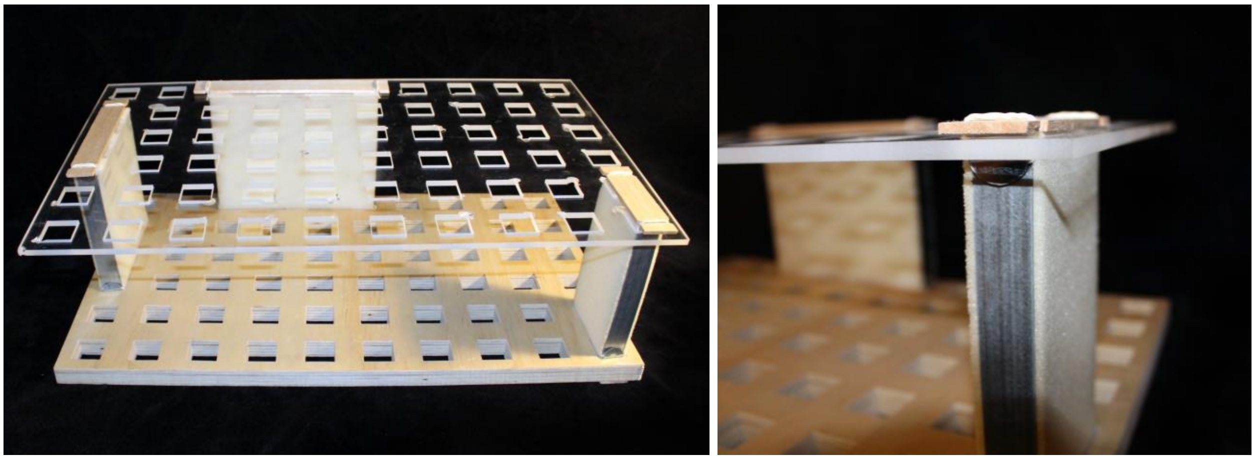
3.5.1 Student Learning Objectives

A multi degree-of-freedom (MDOF) structure explored during the course is a single-story rigid diaphragm structure which can be modeled with two translational and one rotational degrees of freedom taken at the center of mass. Students are taught to derive the stiffness matrix by first determining the lateral stiffness of each wall, brace, or column, and then implementing the direct stiffness method by applying a unit displacement to each degree of freedom to calculate reaction forces. Students use a similar approach to find the mass matrix. Once stiffness and mass matrices are known; students learn to solve the eigenvalue problem to determine eigenvalues (natural frequencies) and eigenvectors (mode shapes).

Students find it straightforward to solve the eigenvalue problem, yet it is difficult for them to understand that the displacements in a MDOF system are a combination of the modal responses. If a structure is oscillating at one of its natural frequencies, the motion is harmonic, and the deformation pattern can be described with that mode shape alone. However, ground motion excitations cause arbitrary displacements. These displacements can be described by the product of the mode shapes and modal displacements (the latter incorporates a modal participation factor that weights the contribution of each mode).

3.5.2 Physical Model

The single story diaphragm model (shown in Figure 3.12) is composed of a rigid plexiglass diaphragm, foam shear walls, and a wood base plate. The plexiglass diaphragm and wood base plate each have a grid of cut-out square sockets to allow the shear walls to be arranged in any configuration. The walls can be made in a variety of lengths and heights, but for the W18 quarter, all walls were 6” tall.



(a) Rigid Diaphragm Model *(b) Connection Detail for Shear Walls*

Figure 3.12: Rigid Diaphragm Model

The walls had to be carefully designed to prevent buckling while also exhibiting negligible out-of-plane stiffness and uplift. To address buckling, the foam walls have 24-gauge steel strips glued to each side and bent 180-degrees at the ends. The steel strips do not extend through the diaphragm or base plate as this would introduce out-of-plane stiffness. With this design, the foam walls experienced uplift when the diaphragm was displaced - the walls would rock as they pulled out of the base plate sockets instead of exhibiting the desired shear behavior. This was resolved by including rubber bands that stretch from the ends of the steel strips, through the sockets in the diaphragm or base plate, and around a horizontal piece of wood. Figure 3.12(b) shows a close-up image of the aforementioned wall details that address buckling, out-of-plane stiffness, and uplift.

3.5.3 Instruction Using Physical Model

For the W18 quarter, this diaphragm model was used in a lecture demonstration. A small unidirectional mass shaker was placed on top of the model, and the input frequency was increased until the natural frequency associated with one of the modes was reached; this was repeated for each of the modes. Because the shaker is unidirectional, it must be placed in different orientations to clearly activate the different mode shapes. To excite the rotational mode shape, the shaker is placed near the perimeter so it shakes perpendicularly to a line (or moment arm) that reaches from the center of rotation to the shaker. For the most effective demonstration, walls should be oriented in such a way that the three mode shapes are easy to distinguish, such as placing the walls in a C shape around the perimeter.

3.5.4 Sample Data Analysis

This is a qualitative observation activity and there is no required data analysis.

3.5.5 Materials List

A miniature mass shaker is used to activate the mode shapes of the rigid diaphragm model, details on this apparatus can be provided upon request as it was borrowed from another instructor. It is also possible to orient the diaphragm in different directions on a shake table to observe mode shapes, or to allow students to apply an initial displacement to initiate free vibration and observe arbitrary motions (which do not correspond with a natural frequency or mode shape). Details on the shake table can be found in Section 3.4.5. Additional materials to construct the rigid diaphragm model are included in Table 3.4.

Table 3.4: Rigid Diaphragm Materials List

Product Description	Dimensions	Supplier	Cost/Unit	# Units	Cost
3/4" Plywood	24" x 24"	Home Depot	$8.72	1	$8.72
1/4" Plexiglass	12" x 24"	Amazon	$23.98	1	$23.98
1" Cushion Foam	36" x 72"	Michael's	$14.99	1	$14.99
Fabric Spray Paint	-	Beverly's	$8.99	1	$8.99
24 Gauge Steel	12" x 24"	MetalsDepot	$9.00	1	$9.00
Rubber Bands	-	Dollar Tree	$1.00	1	$1.00
1/8" Wood	3" x 36"	Michael's	$3.39	1	$3.39
				Total Cost	$70.07

3.5.6 MATLAB Graphical User Interface Animations

Physical models require fabrication time and money, storage space, and set up time prior to a lab session. A virtual model only requires initial computer programming time and can be created with free or low-cost software, requires no physical storage space, and can be quickly customized. Additionally, a virtual model can be distributed to students to experiment with on their own time (as a homework exercise) and can illustrate dynamic concepts that would be difficult to demonstrate with a physical model, such as a structure's response to multi-directional ground motion.

The MATLAB virtual diaphragm model, shown in Figure 3.13, complements the physical rigid diaphragm model described in Section 3.5.2. In W18, students explored this virtual model as an extra credit homework activity. The model allowed them to change the mass and geometric configuration of the diaphragm as well as the locations, heights, and stiffness of columns. The MATLAB script uses student inputs to calculate the mass and stiffness matrices and mode shapes. It also determines the displacement time histories to be able to produce clear 3D animations of each mode shape and the response to the El Centro ground motion without need for a mass shaker or shake table. An instruction sheet can be found in Appendix B.6. The MATLAB scripts, functions, and figures (Newmark's Linear Acceleration Method used for numerical integration, El Centro ground motion data, and visual interface), as well as the MATLAB scripts and raw acceleration data for other activities presented in this report are available upon request.

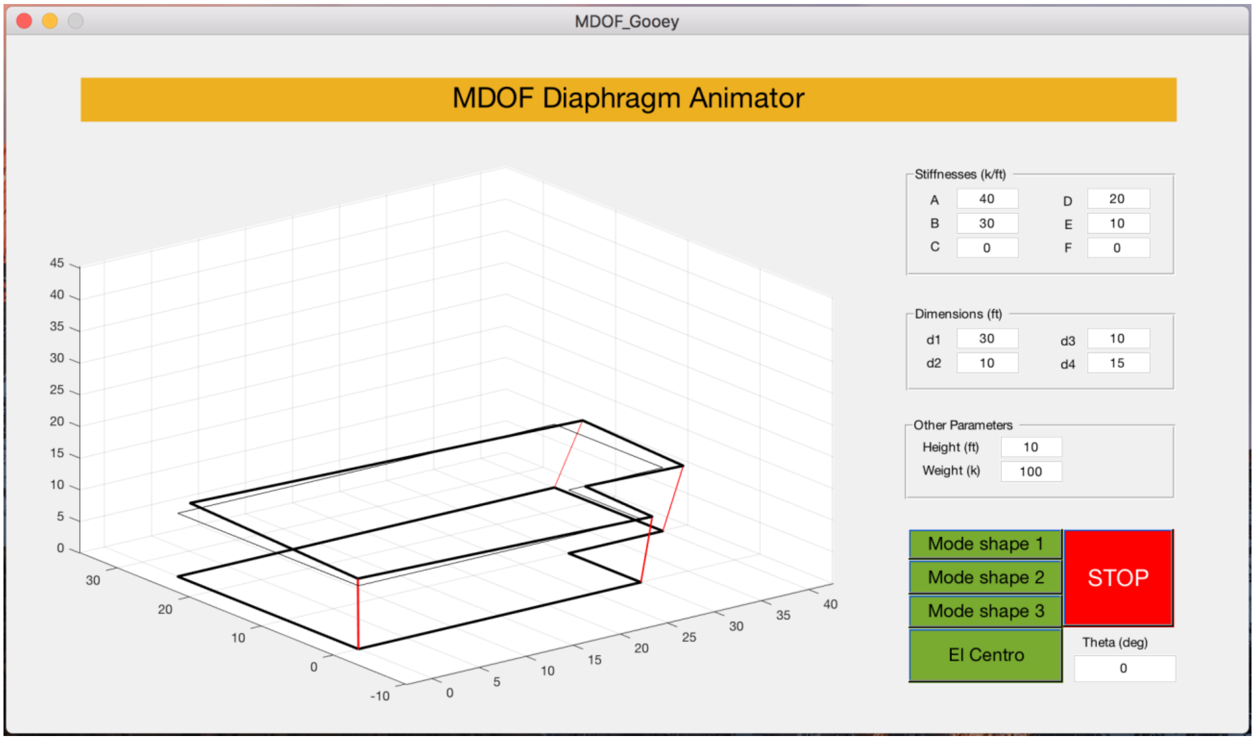


Figure 3.13: MDOF Diaphragm Animator Graphical User Interface

3.6 Multi Degree of Freedom System - Portal Frame

3.6.1 Student Learning Objectives

Portal frame models, with flexible columns and rigid beams, are frequently used as calculation examples when students are learning about dynamics of structures because of their simplicity. A single-story portal frame can be modeled as a single degree-of-freedom structure, and an each additional story adds another degree of freedom. Despite how often portal frames are analyzed in both lecture and lab, there have not previously been a set of 1, 2, and 3-story physical portal frame models used in this class to discuss resonance or mode shapes. These models are easy to construct and provide an excellent visual to accompany the homework problems and in-class exercises.

3.6.2 Physical Models

Each of the 1, 2, and 3-story portal frame models, shown in Figure 3.14, are constructed with 8” story height with the identical mass and stiffness for each floor. The columns are made of 1”x1/16” strips of balsa wood, and the bases are 3”x7”x1/4” balsa wood. Each Jenga block has a 15/64" hole drilled vertically through the center and 1/8” holes drilled horizontally through each end. A bolt is threaded through the center hole to accommodate the use of washers as masses, which can be tightened down with wing nuts. Bolts are threaded through the end holes to accommodate wood braces to lock the floor from moving or rubber bands to serve as braces and increase the story stiffness. A close-up of this construction detail is shown in Figure 3.15(b). Jenga Blocks can either be nailed (or joined with wood glue) to the balsa wood columns; the portal frame is glued to the wooden base plate with wood glue. As a note, this model only requires access to basic hand tools, rather than the water jet cutter commonly needed for the

other models discussed in this document. The author suggests using either shorter story heights or a stronger material for the columns (thicker wood or light gauge sheet metal), as this version of the model was fairly fragile.

Figure 3.14: Set of Three Portal Frame Models

(a) Weight Attachment Detail

(b) Brace Detail

Figure 3.15: Portal Frame Model Construction Details

3.6.3 Instruction Using Physical Models

This model was not implemented during the W18 quarter, but it could be used with or without a shake table. A demonstration without the shake table could be done by taping the bases of the models together so they all experience the same input ground motion. The instructor could then slide the base back and forth on a table and activate the first natural resonant frequency and illustrate the corresponding mode shape for each of the three structures. This clearly demonstrates that structures have distinct responses to the same ground motion depending on their unique natural frequencies.

A similar demonstration could be performed using a shake table, which allows for precisely controlling the input forcing frequency. Additionally, masses could be added to the models in various ways to investigate how modifying this parameter impacts natural frequency and results in different dynamic response. For example, one interesting activity would be to ask students to calculate the stiffnesses of each structure and to estimate how much mass would need to be added to the 1- and 2-story models match the first natural frequency of the 3-story model. Then students could then test their predictions on the shake table, which would serve as a great visual demonstration of the relationship between mass, stiffness, and frequency.

Rigid wood braces or rubber bands could be attached to the horizontal bolts at the ends of the Jenga Blocks at the upper level(s) of the 2- and 3-story models to increase their rigidity, and to demonstrate the behavior of a structure with a soft story at the ground level. This could be followed with a discussion of soft stories and how they are addressed in the building code.

3.6.4 Sample Data Analysis

This is currently posed as a qualitative observation activity with no required data analysis.

3.6.5 Materials List

Shake table is optional, but useful if the instructor would like to implement calculation exercises where natural frequencies need to be accurately determined. See Section 3.4.5 for details related to the shake table. Additional materials to construct the 1-, 2-, and 3-story portal frame models are listed in Table 3.5.

Table 3.5: Portal Frame Materials List

Product Description	Dimensions	Supplier	Cost/Unit	# Units	Cost
Jenga Blocks	-	Target	$10.49	1	$10.49
1/16" Balsa Wood	4" x 36"	Michael's	$2.99	2	$5.98
1/4" Wood Slats (4 pack)	3" x 7"	Michael's	$2.99	1	$2.99
1/4" x 1-1/2" Hex Bolts	-	Home Depot	$0.06	6	$0.36
6/32" x 1-1/2" Elec. Screws	-	Home Depot	$1.30	1	$1.30
#18 x 5/8" Wire Nails	-	Home Depot	$1.67	1	$1.67
5/16" Washers	-	Home Depot	$0.16	30	$4.80
1/4" Wing Nuts (4 pack)	-	Home Depot	$1.18	2	$2.36
Guerilla Glue	-	Michael's	$4.99	1	$4.99

Total Cost	$34.94

4. Student Assessment

Students were asked to complete a survey with 23 multiple choice and 7 free response questions at the end of the W18 quarter. This survey includes questions about the teaching methods in general as well as questions designed to target the effectiveness of the lab activities, physical models, and demonstrations that were implemented during the W18 quarter. Multiple choice questions were organized in two sections: a general section and a section that was specific for the classroom activities discussed in this report. Free response questions ranged from questions about the class and instructor to more specific questions about the use of physical models, demonstrations, or lab activities. All 16 students enrolled in the W18 offering of the course provided consent and completed the survey. The full survey is included in Appendix C.

4.1 Multiple Choice Survey Questions

4.1.1 Selected Multiple Choice Questions Posed

Of the 23 multiple choice questions, 4 of the general questions and 7 specific questions relevant to the physical models, experiments, and demonstrations discussed in this report are shown below.

General Multiple Choice Questions (1-4):

How well does the instructor coordinate the use of physical demonstrations or models in the course?	VERY WELL	5 – 4 – 3 – 2 – 1	POORLY
The physical demonstrations or models provided a valuable visual reference when completing in class exercises, homework, or exams.	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
Hands-on experiments, demonstrations, or models used in ARCE 354 were helpful in understanding structural dynamics concepts.	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
The use of smart phones in lab (ie. accelerometer application) made data collection more interesting and accessible to me.	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE

Specific Multiple Choice Questions:

Please circle the number on the scale which best represents your perceptions of specific class activities, where 5 signifies "Effective/Interesting" and 1 signifies "Ineffective/Uninteresting":

SDOF Free Vibration – Collecting acceleration data for cantilevers of various materials/heights	5 – 4 – 3 – 2 – 1
Damping – Collecting data with triangular, one-story model (sloshing/tuned-mass damper)	5 – 4 – 3 – 2 – 1
Forced Vibration – Conducting frequency sweep on cantilever models using shake table	5 – 4 – 3 – 2 – 1
Dynamic Amplification – Processing frequency sweep data to create an Rd curve	5 – 4 – 3 – 2 – 1
MDOF Diaphragm – Experimenting with a mass shaker on the diaphragm model	5 – 4 – 3 – 2 – 1
MDOF Mode Shapes – Testing 3 story portal frame models on shake table (*video)	5 – 4 – 3 – 2 – 1
MDOF Animations – Experimenting with MATLAB GUI to visualize mode shapes (*HW7)	5 – 4 – 3 – 2 – 1 or N/A

4.1.2 Analysis of Selected Multiple Choice Questions

General Multiple Choice Questions

The questions in the general sections are aimed at gauging how effective, useful, or engaging the lab activities, models, and demonstrations were, without focusing on any individual activity. Of these four questions, all sixteen students answered questions 1, 2, and 4. One student did not select a response for question 3. The distribution of student responses is plotted in Figure 4.1.

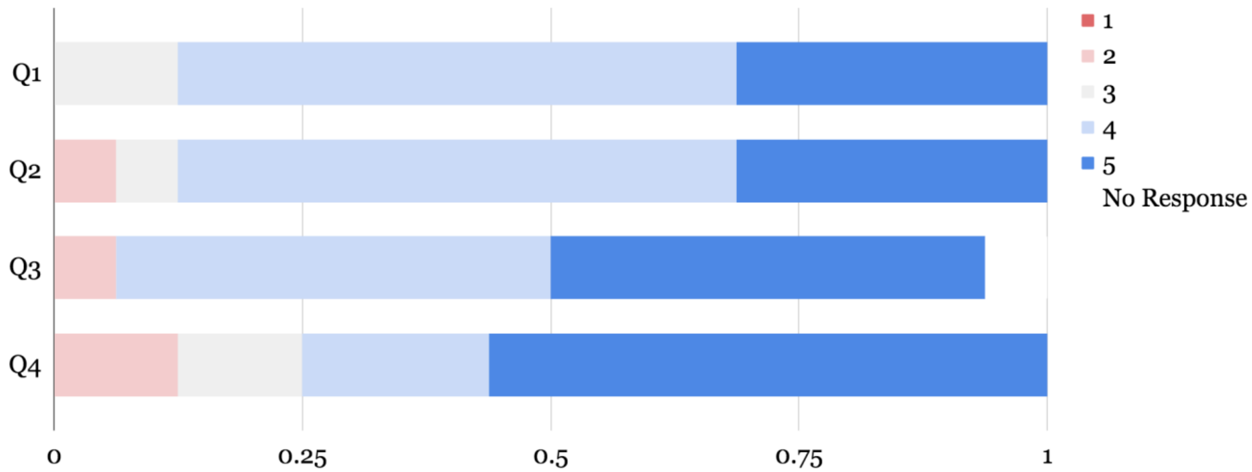


Figure 4.1: Likert Scale Distribution of Student Responses to General Multiple Choice Questions, Where 5 Indicates a Very Positive Response and 1 Indicates a Very Negative Response

The responses were primarily positive or very positive for every question. Of the sixteen students, fourteen (87.5%) indicated that the instructor implemented the models well or very well, for an average response of 4.19 for the first question. A similar distribution appears for the second question, which asks the students to indicate their level of agreement that the physical experiments, models, or demonstrations were a useful reference when completing assignments, for an average response of 4.13. The third question asks whether the physical experiments, models, or demonstrations were helpful in understanding structural dynamics concepts. Fourteen of the fifteen responses were either positive or very positive, for an average of 4.33. The final question asks students about the use of the smartphone accelerometer application. While 12 of 16 students (75%) rated this experience with new technology as positive or very positive, with an average of 4.19, the authors suspect that the negative and neutral responses might be due to difficulties using the application. Some students reported that the application truncated or deleted their data inadvertently and they had to re-record the data.

Specific Multiple Choice Questions

Students selected a number between 1 (Ineffective/Uninteresting) to 5 (Effective/Interesting) for each physical model, lab activity, or demonstration described in this document. The forced vibration lab activity described in Section 3.4 was divided into two questions for the survey as students experimented with the shake table without recording any acceleration data and were then given an Excel file with the acceleration time histories for a range of forcing frequencies to process with MATLAB.

The question regarding the MDOF mode shapes for portal frame refers to two videos of frequency sweeps (conducted by Professor Oh-sung Kwon while at Missouri S&T) rather than the models described in Section 3.6, as the fabrication was still being completed during the W18 quarter. Links to those videos are included in Appendix B.5 (Homework #7).

All sixteen students provided responses for five of the seven questions, and fifteen students responded to the question regarding the rigid diaphragm activity. The final question has a lower response rate of just thirteen students (81.25%). The lower response rate results from the fact that use of the MATLAB Graphical User Interface was assigned to students as an extra credit activity in Homework #7.

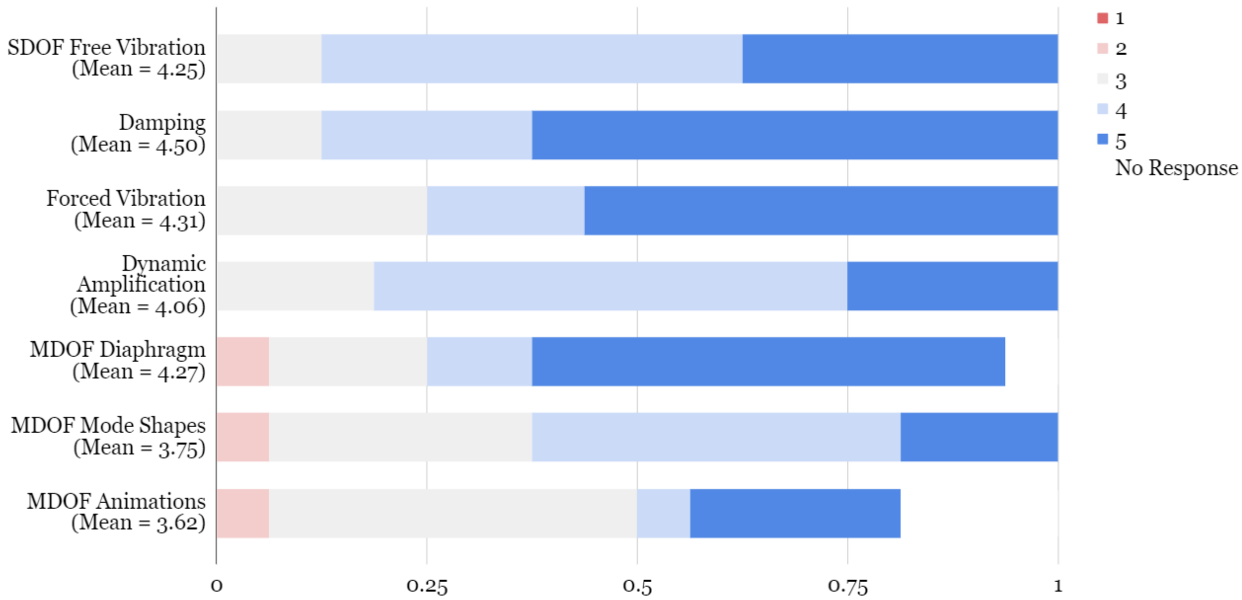


Figure 4.2: Likert Scale Distribution of Student Responses to Specific Multiple Choice Questions, Where 5 Indicates a Very Positive Response and 1 Indicates a Very Negative Response

The responses are generally positive, with only three negative responses total; however, there are many more neutral responses than there were for the more general questions. The questions here are ordered chronologically, and as the quarter progresses the rigor and speed of the course continues to increase. Furthermore, some of the later MDOF activities are observational (or optional), rather than hands-on experiments conducted by the students themselves. This may explain the trend seen in Figure 4.2, where the responses are mostly positive for the earlier lab activities, and wane slightly in later activities.

4.2 Free Response Questions

The survey included seven free response questions, three of which ask specifically about the physical models, lab activities, or demonstrations discussed in this document. Other questions, while more general, may still receive responses that are relevant. Selected responses that pertain to the models and activities discussed in this document have been divided into five categories ranging from very positive to very negative.

Students' survey comments which were categorized as "very positive" often focused on the distinction between theoretical concepts and *learn by doing* approaches to gaining a foothold on the material.

Students expressed that much of their understanding came from physically doing or seeing things. In addition to increasing their engagement with class topics, students said that the hands-on activities were genuinely enjoyable as well. A few selections from this category include:

> "I loved [the physical models, demonstrations, and/or experiments]! Visually seeing the concepts we discussed was incredibly beneficial because I am a visual learner."

> "The [physical models, demonstrations, and/or experiments] we had were very interesting. Just seeing how systems reacted really helped me in solving my calcs with more understanding."

> "I found that that lab experiments were very helpful in explaining concepts. Keep these! Or even create more"

Comments which were categorized as "positive" were not dramatically different from the comments in the "very positive" category. Students in this category found lab activities to be helpful to their learning, but also mentioned that much of their learning comes from homework, or that they would have liked more activities. A few selections from this category include:

> "The homeworks and hands-on experiments [have been the most beneficial aspects of this course]. I found that the homework helped a lot with understanding the roles of variables and the experiments helped me with visualizing what is happening in my calcs."

> "Hands-on experiments [and] anything that is related to reality & industry [have been the most beneficial aspects of this course]."

> "[I would have liked] more experiments. The application of the El Centro data was great in increasing understanding and application."

Students' survey comments which were categorized as "neutral" weighed the pros and cons of the models and activities. It seems that students in this category enjoyed the models and activities, but recognized areas that could be improved in the future. A few selections from this category include:

> "The physical models were well-made and worked very well. They were imaginative! The tuned mass damper could maybe have been built a little better, it kept hitting the structure when we used it in lab."

> "Strengths: Visual understanding, it isn't too often I get to watch structures being shaken with a known value. Weaknesses: Too short of time spent on them."

Students' survey comments which were categorized as "negative" tended to address the complexity and time involved in both the lab experiments and models. One issue that came up in several comments was a feeling of unequal involvement in class activities. Notably, some students also found data collection to be problematic, either in the use of accelerometer application or in the logistics of sharing it with other students. A few selections from this category include:

> "Models were very helpful to those who were involved, but sometimes we need to spend a lot of time giving everyone time with the models."

> “Some of the experiments didn’t have enough material for everyone to work with. Demonstrations were generally pretty short.”

> “Sometimes the data collected from experiments would be altered due to human error, but because the final results are unknown, the incorrect data would go unnoticed until a ‘correct’ solution has been shown to us.”

There was only one student’s survey comment categorized as “very negative.” The student wrote:

> “Models (especially the one with the steel plate base) were not [high quality construction]. A lot of improvement possible which will also increase quality of results.”

Overall, the responses were mostly positive. The only “very negative” comment is mainly referring to the issue with fixity of cantilevers to the steel base of the model discussed in Section 3.2, which has already been addressed. The revised model was implemented in the S18 quarter, and the fixity problem has been completely eliminated. Other “negative” comments were focused on very minor issues with model fabrication, or on the logistics of the model’s implementation. Many of the comments categorized as negative were in response to a question asking specifically how the models could be improved, a question asking for critical feedback.

4.3 Lessons Learned

After analyzing the students’ multiple choice selections and responses to the free response survey questions, the lessons to take away can be condensed to:

- Students’ educational and personal experiences in class are enriched through visual and physical engagement with the models in lab experiments. Showing a video can be very effective at giving students a visual reference, but letting students experiment hands-on with physical models is a more effective way to build intuition about the structural behavior. The students expressed that they enjoyed these activities and that the activities improved their understanding of the concepts.
- Students seek to connect their theoretical learning with the real world. Incorporating physical experiments into the course gives students the opportunity to use the equations taught in class to predict the behavior of a physical model, which they can compare to the experimental results. This comparison of theoretical and experimental results is not only engaging, but it makes students more confident that those equations are valid.
- Regular homework and testing is also important to ensure that students retain theoretical material underlying the lab experiments. Labs are not meant to be a substitute for homework or tests, but rather a supplement.
- Most “negative” comments were related to time management during the implementation or the construction quality of the models. Even the students who wrote “negative” comments agreed that the inclusion of these hands-on activities was beneficial to their learning. Both timing and modifications to improve the performance of hands-on models have been addressed for the S18 offering of the course and should be carefully addressed by other instructors who wish to implement the activities described in this report.

5. Outline of Future Work

The physical models were designed, fabricated, and implemented in the classroom in just one academic quarter. Design is an iterative process, and with such a fast-paced development process, there are bound to be areas of improvement on the models. Despite the short time period available for development, the models were highly effective. Students expressed that they found the models interesting and helpful for learning concepts. In future quarters, the continued use of these models and activities will bring ideas for improvement to light, which will facilitate the development of more refined models and activities for the structural dynamics lecture and lab course pairing.

Acknowledgements

The authors would like to thank the California Polytechnic State University support shop technicians: Vince Pauschek, Dave Kempken, and Tim Dieu, for helping with the design and fabrication of the steel base of the cantilever model. Thanks also to Jack Hazen, the water jet cutter technician, for his extensive help with fabrication of many of the model parts as well as Professor Peter Laursen for lending his mass shaker to be used with the rigid diaphragm model. The authors also appreciate the contributions of students who participated in the study under IRB Approval # 2018-075-CP from the California Polytechnic State University – San Luis Obispo.

References

[1] Chopra, A.K. (2016), Dynamics of Structures, 5th Ed.

Appendix

A Course Syllabi

A.1 ARCE 354 W18 Syllabus

California Polytechnic State University
Winter Quarter 2018

ARCE Department
Instructor: Dr. Anahid Behrouzi

ARCE 354 Numerical Analysis Laboratory

In partnering with the structural dynamics lecture, this lab is intended to provide a strong understanding of relevant numerical analysis techniques and experimental methods.

Professor: Dr. Anahid Behrouzi
(Information Redacted)

Office Hours:

Prerequisites:

Co-requisites: ARCE 412 Dynamics of Framed Structures

Textbook: none

Student Learning Outcomes:

During the quarter, we will learn how to implement various numerical analysis techniques that support our structural engineering problem-solving, including:

- Numerical integration
- Solution of Ordinary Differential Equations
- Solution of Nonlinear Equations
- Solution of Symmetric Eigenproblems (via various approaches including determinate search)

Additionally, we will learn how to collect and analyze dynamic response data for various small-scale structures using sensors/applications available on most smart phones.

A.2 ARCE 412 W18 Syllabus

California Polytechnic University
Winter Quarter 2018

Architectural Engineering Department
Instructor: Dr. Anahid Behrouzi

ARCE 412 Dynamics of Framed Structures

In your architectural engineering careers, you will find that there are many natural and man-made forces that dynamically excite structures – that may cause minor vibrations to more significant damage. Therefore, it is important that you are able to design buildings that not only meet serviceability requirements, but also are resilient. Although the use of computers and structural analysis/design software are ubiquitous in industry, this course is intended to help you develop your human insight into structural dynamics that will allow you be an active thinker in the design process and to assess the accuracy of the computer analyses you conduct for complex structures. My goal with this course is to help nurture your engineering sense, both in terms of theory and "hand-solution" methods (ARCE 412) and state-of-the-art technology (ARCE 354).

Professor: Dr. Anahid Behrouzi
(Information Redacted)

Meeting Times:

Office Hours:

Prerequisites:

Co-requisites:

Textbook: Dynamics of Structures (fifth edition), by Anil K. Chopra, Pearson Prentice-Hall, 2017. ISBN 978-0-13-455512-6.

Student Learning Outcomes:

During the quarter, we will learn how to analyze single and multi-degree of freedom structural systems. By the end of the course, we will have gained mastery in:

- Developing a dynamic mathematical model and equation of motion to describe systems
- Determining response of system under free vibration and forced excitation (harmonic/periodic; arbitrary, step, and pulse; and general/time-varying loadings)
- Analyzing structures subject to earthquake/support excitation
- Implementing modal analysis to evaluate the response of multi-degree of freedom systems

Course Content:

Week	Topic	Text
1	Introduction and Review	1.1-1.11
2	Free Vibration	2.1-2.2
3	Forced Vibration	3.1-3.2
4 and 5	Numerical Evaluation (ARCE 354)	4.1-4.2,5.1,5.4,5.5
4	Earthquake Response	6.1-6.8
5 and 6	Multiple Degree of Freedom (K&M)	9.1-9.5
7	MDOF Free Vibration	10.1-10.8
8 and 9	Modal Analysis	12.1-12.7
10	Earthquake Analysis	13.1-13.9

B Assignments and Supplementary Material

B.1 Lab Assignment 1

California Polytechnic State University
Winter Quarter 2018

ARCE Department
Instructor: Dr. Anahid Behrouzi

ARCE 354 Numerical Analysis Laboratory

Lab Assignment 1: Due at the beginning of the next lab session

A hard copy of the lab report is due to the instructor and Matlab .m/.mat files are due to PolyLearn

General:

In this lab, students will explore how the dynamic response of a simple cantilever structure is affected by material type (steel, Plexiglas, and wood) and three lengths each material (12", 18", and 22"). This will be explored via calculated predictions using test specimen geometries and approximate material properties as described below in ***Part 1***. Students will compare calculated values with results of experimental tests described in ***Part 2*** where the cantilever is subjected to some initial displacement and the acceleration time history, $\ddot{u}$, is recorded with a smart phone app; this data will be subsequently plotted and compared in MATLAB.

This lab will be conducted in groups of three where each team member is responsible to complete the hand calculations and experimental tests for one material type of the available lengths. Group members will need to share calculated and experimental results with other group members, so each student can make comparisons between all the material types in their lab report.

Specific Problem:

Part 1: Hand Calculations

1. Use a ruler or tape measure to measure the width, b, and the length, L, of each test specimen (to the nearest 1/32"). For length, measure from the lower notch (which will be flush with the top of the base plate) to the "free end". Thickness, t, for each specimen was measured with a dial caliper and is noted in Table 1 below.
2. Use a scale to weigh, in lbs: (i) each test specimen and (ii) phone, phone mount, and hardware. Divide the weights by gravity = 386.4 in/sec^2 to determine mass. The lumped mass, M, at the "free end" will be taken as the sum of half the specimen mass plus the total mass of the assembly of phone and phone mount.
3. Calculate the stiffness (lb/in) for each set up. Use an approximate elastic modulus value, E, noted in Table 1 below. Recall that for a fixed-free member, $k = 3EI/L^3$.
4. Calculate the natural circular frequency (rad/sec), for each set up using $\omega_n = \sqrt{K/M}$.
5. Calculate the natural period (sec) for each set up using $T_n = 2\pi/\omega_n$. The natural period is approximately equal to the time it takes to complete one complete cycle of oscillation for an lightly damped system.
6. To summarize the measured and calculated values from Steps 1-5, fill in the table below:

   Total Mass = (Mass of phone + Mass of phone mount + ½ Mass of Specimen)

Table 1. Measured and Calculated Values for Each Cantilever Specimen

Material	Approx Length (in)	Estimated E (psi)	t (in)	b (in)	L (in)	I (in^4)	K (lb/in)	Specimen M (lbs-sec^2/in)	Total M (lbs-sec^2/in)	ω_n (rads/sec)	T_n (sec)
Steel	12"	29000 x 10^3	0.059								
	18"										
	22"										
Plexiglas	12"	460 x 10^3	0.197								
	18"										
	22"										
Wood	12"	1900 x 10^3	0.290								
	18"										
	22"										

Part 2: Experimental Testing

1. Have at least one group member download the smart phone accelerometer app. Refer to the "iPhone Accelerometer Tutorial" for specific instructions.
2. Set the member into the slot and tighten it into place.
3. Attach the phone mount and phone at the top of the cantilever.
4. Start the accelerometer, collect a few seconds of data for the system at rest to establish a baseline. Then displace the top of the member and release it.
5. Once the member stops oscillating, stop the accelerometer and email the data to yourself and share with other team members.
6. Refer to the "Accelerometer Phone App" tutorial for specific instructions on importing data into MATLAB.
7. Refer to notes from class demonstration on MATLAB plotting to produce a single plot with the acceleration time history records for your material type to compare the response of the 3 different cantilever lengths (12", 18", and 22"). Determine the natural period T_n from the plots using the definition from Part 1: Step 5.
8. Using the data provided by your group members, create a single plot the acceleration time history records for all 22" specimens to compare the response of the 3 material types (steel, Plexiglas, and wood).

Submittal:

Each team member should independently produce a typed lab report addressing Part 1 & 2 above, and includes:

- A brief introduction paragraph ≥ 3 sentences describing the purpose of the lab.
- 1-2 sentence description of the experimental set-up with labeled photograph(s).
- A summary table like that shown in Table 1 that ***also*** includes ω_n and T_n determined from the acceleration time history plots , $\ddot{u}$. In support of the summary table, provide a hand-solution for Part 1: Steps 2-5.
- The two acceleration time history plots, $\ddot{u}$, described in Part 2: Steps 7 – 8. In support of the plots, provide a copy of the MATLAB script used.
- 2-3 sentence description commenting on the difference in dynamic response resulting from changes in specimen height and material type.
- A 1-2 sentence commentary on potential sources of error between the calculated and measured ω_n and T_n.
- A brief conclusion paragraph ≥ 3 sentences describing the successes and challenges of the lab, questions you have, suggested improvements, etc. (example: "I found this lab to be informative, or not, because of…; I found new confidence in my ability to…; The most, or least, interesting part of the lab was…, etc).

Lab Assignment 1 was developed in conjunction with Charles D. Facciolo in partial fulfillment of his ARCE Senior Design project.

Acknowledgements for assistance with fabrication of experimental set-up and specimens to CAED shop staff: Vince Pauschek, Tim Dieu, and Dave Kempken.

B.2 Accelerometer Tutorial

California Polytechnic State University
Winter Quarter 2018

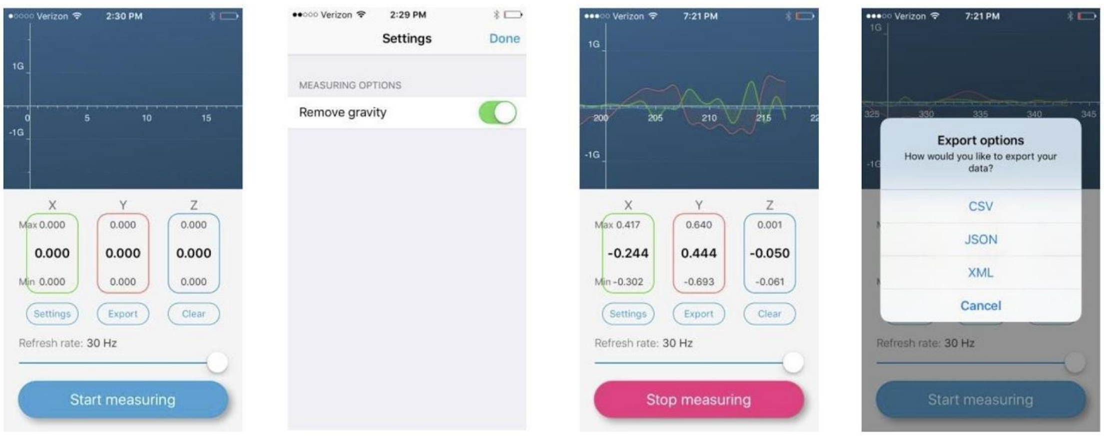
ARCE Department
Instructor: Dr. Anahid Behrouzi

ARCE 354 Numerical Analysis Laboratory

iPhone Accelerometer Tutorial

1. Download the app "Accelerometer" from the app store by searching for "accelerometer dreamarc".

2. Open the application
   a) Set the refresh rate to 30 Hz
   b) Under "Settings" turn on "Remove gravity"
   c) When you are ready to record data, select "Start measuring"
   d) When you have finished recording, select "Stop measuring"
   e) Select "Export" and email yourself the data in CSV format (Comma Separated Values)



3. If you are using a Windows computer:
   a) Copy the data that you emailed yourself excluding the first row of words (index;x;y;z) and paste into a new Microsoft Excel sheet.
   b) Select the first column of data, proceed to the "Data" tab, and choose the "Text to Columns" option. Leave the pre-selected "Delimited" type and press Next>, mark the checkbox next to "Semicolon" so that it is selected along with "Tab". Press Next> and then Finish. There should now be four separate columns of data.
   c) Save the file in .xlsx format.

4. To import this data into MATLAB:
   a) Under the "Home" tab, select "New Variable". Copy the column of entries for the correct acceleration direction from your spreadsheet and paste into the blank variable that appears in MATLAB.
   b) Rename the variable by right-clicking on the unnamed variable in the Workspace, selecting rename, and giving it a name (example: Wood12in).
   c) After loading all of your data as individual variables representing each acceleration time history for your material type (example: Wood12in, Wood18in, Wood22in). Then select "Save Workspace" and name the collection of variables as a .mat file (example: Wood). Share this with your teammates.

5. To plot the data using MATLAB:

a) First, create a new script in the “Home” tab by selecting “New – Script”. Name and save the script in the same folder location as your .mat files that contain the data you will be plotting.
b) Start your script with the standard clear protocols and then load the necessary .mat files.

```
close all; clear all; clc;
load('Wood.mat')
```

c) Create a time vector, you can divide the values in the first column by the frequency at which the data was recorded, which should be 30 Hz.

```
Hz = 30; % The frequency (Hz) at which the data was recorded
t = (1/Hz)*Wood(:,1); % Time vector in seconds
```

Now you have the acceleration data in each direction and the corresponding time in seconds as its own vector.

d) The following space is for you to take notes on plotting:
   - Plotting multiple lines on a single graph

   - Modifying linetype and color

   - Adding a title and axes labels

   - Adding a legend and setting the location of the legend

   - Saving the figure so it can be pasted into a Microsoft Word document

Lab Assignment 1 was developed in conjunction with Charles D. Facciolo in partial fulfillment of his ARCE Senior Design project.

B.3 Lab Assignment 3

California Polytechnic State University
Winter Quarter 2018

ARCE Department
Instructor: Dr. Anahid Behrouzi

ARCE 354 Numerical Analysis Laboratory

Lab Assignment 3: Due at the beginning of the next lab session

A hard copy is due to the instructor and Matlab .m files are due to PolyLearn

General:

Damping, a structure's ability to absorb energy generated by external excitations. Most structures we are concerned with have an inherent (natural) damping ratio, $\zeta < 0.10$ or 10%, resulting from internal friction of materials and connections. More slender, high-rise structures are typically assumed in the range of 1-2% which can result in these systems being "dynamically sensitive" or "susceptible to vibrations" (Robinson et al. 2007). There are variety of supplemental passive control devices for increasing damping and decreasing vibration resulting from wind or earthquake vibrations in high-rise buildings. Some examples include tuned mass dampers (TMDs) and tuned liquid dampers (TLDs) – also referred to as sloshing liquid dampers (SLDs). These damping approaches do not just reduce displacements (serviceability or material fatiguing concerns), but also can reduce overall force and floor accelerations.

Part 1: Students will collect data using a smart phone accelerometer introduced during Lab Assignment #1 to plot the acceleration time history in MATLAB.

Part 2: Students will use measured system material/geometric properties and recorded acceleration time histories from Scenarios (a-c) below to: (1) calculate the damping from the experimental data with logarithmic decrement "log-dec" method, (2) determine the equation of motion for damped free vibration, and (3) plot the idealized displacement time history using the calculated alternate (short) form of u(t) using $u_o = 2$ inches and $\dot{u}_o = 0$ in/sec.

Specific Problem:

Part 1:

1. Each team will be recording accelerometer data using the phone app for one of the five different conditions:
   a) Locked pendulum with no weights attached
   b) Scenario (a) PLUS slotted weights fixed on the top of the structure
   c) Scenario (a) PLUS weights fixed on the locked pendulum
   d) Unlocked tuned mass damper with weights attached
   e) Tupperware filled with water to match the weight of the slotted weights
2. For each of the conditions, 1(a-e), use a ruler to apply an $u_o = 2$ inches initial displacement. Upon release, the structure will exhibit a damped free vibration response.
3. Use the same amount of weight for each of the conditions (excluding 1a). Be sure to record this weight. Use a ruler to measure and record the length of the pendulum from the center of the hinge to the center of mass of the weights. For the sloshing damper, fill the container so that its weight is equal to that of the masses used.

   For weights, see the back of the following page.

Part 2:

1. Open the acceleration data in MATLAB and create acceleration time history plot for each condition.
    a. Implement "spline" in MATLAB to smooth the data curves.
2. Utilizing the acceleration time history plot, implement logarithmic decrement method and determine the damping coefficient, c, and the damping ratio, ζ, for Scenarios (a-c) only.
    a. Use distance between multiple peaks and average to find damping.
3. Determine the equation of motion for damped free vibration for Scenarios (a-c) only.
4. Plot the idealized damped free vibration – the alternate (short) form, u(t) – for Scenarios (a-c).

Submittal:

You should produce a typed lab report that includes:

- A brief introduction paragraph ≥ 3 sentences describing the purpose of the lab
- Experimental acceleration time history plots for Scenarios (a-c).
- Complete hand or MATLAB solution for the system stiffness, mass, damping ratio and coefficient of damping for Scenarios (a-c). Tabulate these values along with both the natural and damped circular frequencies and periods for these systems. Use the spreadsheet from Lab Assignment #1 as a model.
- Write out the equation of motion for Scenarios (a-c) as well as alternate (short) form expressions for displacement time history, u(t).
- Idealized displacement time history, u(t), plots for Scenarios (a-c).
- Comment 2-3 sentences on the damping values determined for Scenarios (a-c) as well as the damping trends you observed qualitatively/quantitatively with the response for Scenarios (d-e).
- A brief conclusion paragraph 3-5 sentences describing the successes and challenges of the lab, questions you have, etc.

The wooden mass at the top of the triangle weighs 4.445 lbs. Additional assembly parts are listed below:

	Weight		
Part Description	Lb	Oz	Lb (decimal)
Top cross w/ phone mount	0	9.9	0.619
Bottom T w/ nuts+bolts	0	5.6	0.350
Pendulum w/ nut+bolt	0	2.2	0.138
Pendulum seat w/ nut+bolt	0	2	0.125
Unlocked Assembly w/out weights	1	3.7	1.231
Tupperware w/out lid	0	2.2	0.138
Tupperware lid	0	0.8	0.050
Tupperware Assembly w/out water	0	3.1	0.194
Weights (each)	0	7.8	0.488
1 nut + 1 bolt (to lock)	0	0.4	0.025

A reference on Tuned Liquid Dampers (TLD), "Supplmental Damping and Using Tuned Sloshing Dampers" by Robinson et al. 2007 for *Structures* Magazine: http://www.structuremag.org/wp-content/uploads/2014/09/C-Prac-Sol-Tuned-Liq-Dampers-Robinsonpac-5-11-071.pdf

Lab Assignment 3 was developed in conjunction with Charles D. Facciolo in partial fulfillment of his ARCE Senior Design project.

B.4 Lab Assignment 4

California Polytechnic State University
Winter Quarter 2018

ARCE Department
Instructor: Dr. Anahid Behrouzi

ARCE 354 Numerical Analysis Laboratory

Lab Assignment 4: Due at the beginning of the next lab session

A hard copy is due to the instructor and Matlab .m files are due to PolyLearn

General:

Understanding the concept of the dynamic amplification factor (R_d) is an important distinction from your previous structural analysis classes where you calculated displacements and forces (axial, shear, moment) due to ***static*** loads. We use R_d multiplied by those static values to understand our displacement or force due to ***dynamic*** excitation. R_d varies based on the level of damping of a structure, as well as how close the forcing frequency ($\bar{\omega}$) is to the dominant natural frequency of the structure (ω_n). This can be described by the frequency ratio ($\beta = \bar{\omega}/\omega_n$) where $\beta = 1$ indicates that the forcing frequency matches the structure's dominant natural frequency…RESONANCE!

Specific Problem:

Part 1: Students will observe the shake table experiment where we will conduct a frequency sweep for two different height steel cantilevers, these are identical to the cantilevers from Lab Assignment 1. Take qualitative notes on the response of these cantilevers at different frequencies.

Part 2: Students will use acceleration time history data collected for a frequency sweep of 0.5, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90, 0.95, 1.00, 1.05, 1.10, 1.15, 1.20, 1.30, 1.40, 1.50 and 1.60 Hz in order to develop a plot in the frequency domain and determine a structure's dominant natural frequency.

This is for the 22 inch tall steel cantilever specimen; note that the mass of the structure (w/phone + attachments) and the amplitude of shaker remains constant at 0.1 inches for all frequencies.

Use the Matlab instructions provided in class in order to be able to import data from the provided Excel sheet and plot in the frequency domain, students should plot x-axis as Frequency (Hz) and y-axis as maximum normalized acceleration associated with each frequency ($\ddot{u}/\ddot{u}_{max}$) where $\ddot{u}_{max}$ is the maximum acceleration associated with the natural frequency.

Part 3: Students will create approximate R_d curves for a single DOF system with weight of 10 kips, total lateral stiffness of 30.6 k/in, harmonic forcing function of $p(t) = 5sin\bar{\omega}t$, and varied damping ratios of ζ = 2, 5, and 10%. Students should include plots of R_d vs. $\beta = \bar{\omega}/\omega_n$ and use the plots to calculate the maximum (steady state) amplitude of vibration for the 5% system at $0.80\omega_n$ and $1.00\omega_n$.

Submittal:

You should produce a typed lab report that includes:

- A brief introduction paragraph 3-5 sentences describing the purpose of the lab
- Discussion of frequency sweep test setup and execution, as well as observed response of the two cantilevers. Should include labeled photo and 3-5 sentences
- Plot of Frequency vs. maximum normalized acceleration for the frequency sweep in Part 2
- Fully labeled plot of R_d vs. $\beta = \bar{\omega}/\omega_n$ for Part 3; 1-2 sentence discussion of observations with respect to changes observed as damping ratio or frequency ratio changes.
- A brief conclusion paragraph 3-5 sentences describing the successes and challenges of the lab, questions you have, etc.

Lab Assignment 4 was developed in conjunction with Charles D. Facciolo in partial fulfillment of his ARCE Senior Design project.

B.5 Homework Assignment 7

Homework #7

Deadline: Friday, March 16, 2018

Name________________________________

Dynamics of Framed Structures
ARCE 412 – Winter 2018
Cal Poly – San Luis Obispo

Reading Assignment/Multimedia Assignment (15 points)

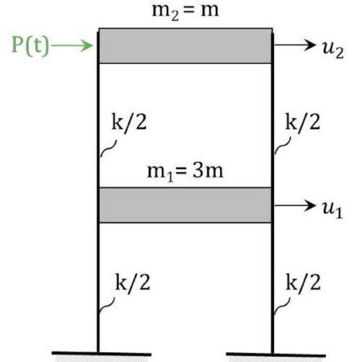
1. Based on class notes and **Chapter 13**, explain the differences in the response history analysis (RHA) and response spectrum analysis (RSA). How does the solution approach as well as the final result differ?

2. Based on **Section 13.7**, investigate different approaches to combine modal response:
   a) When is the SRSS approach appropriate to use? When is it inappropriate?
   b) What is the alternative to SRSS that applies to more types of structures? How does it differ from SRSS?

3. Since we did not get to conduct a frequency sweep on a MDOF in ARCE 354, watch sweeps conducted by Professor Oh-sung Kwon (while at Missouri S&T):
   a) 3-DOF system showing Mode 1 & 2: https://www.youtube.com/watch?v=OaXSmPgl1os, based on the reported natural frequency (Hz) for each resonant mode, calculate the associated T_n. Draw an approximate deformed shape for each mode showing relative displaced shape and occurrence of node(s).
   b) Three SDOF of identical mass/different heights: https://www.youtube.com/watch?v=LV_UuzEznHs, based on the reported natural frequency (Hz) for resonance, calculate the T_n for each structure.

4. **(5 pts extra credit)** Download folder titled "Diaphragm Mode Shape Visualization Tool" from PolyLearn; use a recent version of Matlab (some older versions have difficulties running this file). Experiment with a few diaphragm geometries/weights and column locations/stiffnesses in the tool.
   a) Select one of your designs: sketch the undeformed shape with weight, height, dimensions, and stiffnesses annotated. Sketch the three mode shapes.
   b) Observe how the diaphragm behaves under the El Centro ground motion. Provide feedback on the strengths and weaknesses of the tool that was designed to help you understand diaphragm response.

Calculation Problems (85 points)



k=25 k/in, m=0.05 k-s^2/in, $\zeta = 0$ %
Partial solution: ω_1=10.78, ω_2=26.78

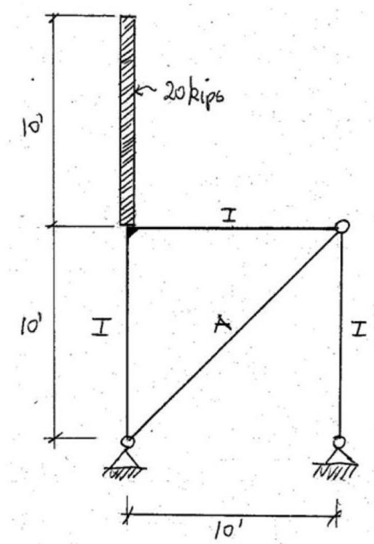
Calculate and **plot** the response of ***u(t)*** for the structure at the left given the following scenarios (t=0-2 secs). The calculation should be a hand solution, and plots should be generated in MATLAB following ARCE 354 guidelines.

1. Initial conditions: $\mathbf{u(0)} = \begin{Bmatrix} 1.0 \\ 2.5 \end{Bmatrix}$ in and $\dot{\mathbf{u}} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$ in/sec.

2. Harmonic load **P (t)** = 12 sin (8t) at the top mass only.

3. Step force **P (t)** of 25 kips at the top mass only.
   Refer to Chopra 5th edition: Fig. 4.3.1 and Eqn 4.3.2.

Next page →



4. The steel structure to the left (pinned base and buckling restrained brace) has 5% damping and is subject to the El Centro ground motion:

a. Calculate the ω_n and ϕ_n, sketch mode shapes

b. Use the response spectrum in Chopra Fig. 6.6.6. Determine maximum:

i) base shear

ii) roof displacement (horizontal beam)

iii) horizontal displacement at top of rigid mass

iv) moment in left column

Note: Beams and columns are axially rigid, I = 20 in^4. For brace: A = 0.5 in^2

Observe: Problems 1-3 deal with RHA, and Problem 4 with RSA.

B.6 MATLAB GUI Tutorial

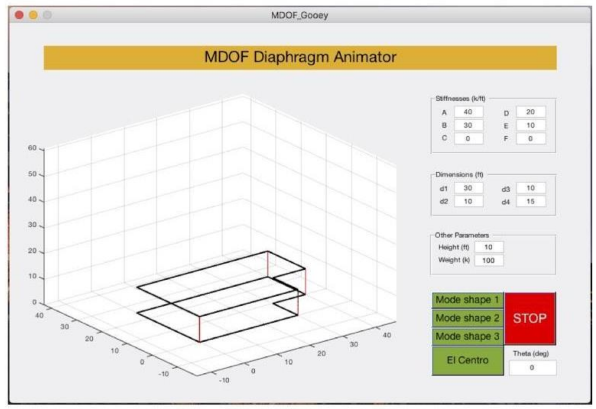
California Polytechnic State University
Winter Quarter 2018

ARCE Department
Instructor: Dr. Anahid Behrouzi

Diaphragm Dynamic Response Visualization Tool

MATLAB GUI Tutorial

General Use:

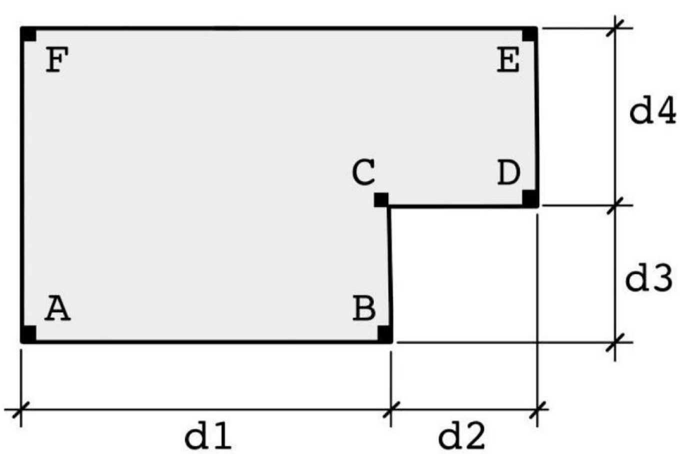


1. Download the folder titled "Diaphragm Dynamic Response Visualization Tool" from PolyLearn.
   a) Open the file titled "MDOF_Gooey.m"
   b) Click run for the user interface appear.

2. Click the different buttons at the bottom right to see animations of the structure.
   a) Click the "Mode shape" buttons to animate the mode shapes 1-3.
   b) Click "El Centro" to animate the structure's response to the El Centro ground motion.
   c) Click "Stop" to stop the animation.
   d) Adjust the value for "Theta" next to "El Centro" to change the angle of the ground motion.

3. The key plan below shows the column and dimension labels. Reference this key plan when adjusting the column stiffnesses, diaphragm dimensions, diaphragm weight, and column heights.
   a) To exclude a column, set the stiffness value to zero.
   b) To make a rectangular diaphragm, set both d2 and d3 to zero. This will make columns B, C and D coincide at the same location, so two of B, C, D stiffness should be set to zero (otherwise the stiffnesses will be combined into one column at that location).

Key Plan:



This diaphragm dynamic response visualization tool was developed by Charles D. Facciolo in partial fulfillment of his ARCE Senior Design project.

C Student survey

Student Survey for ARCE 412/354, WINTER 2018 **Research Consent (Circle One): YES NO**
Instructor: Dr. Anahid A. Behrouzi

The purpose of this survey is to evaluate your experience in ARCE 412 and ARCE 354. Thank you for taking time to provide comments. Please circle the number on the scale which best represents your perceptions:

The instructor is well-prepared for each class session.	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
The instructor's explanation of the materials is:	EXCELLENT	5 – 4 – 3 – 2 – 1	POOR
The pace and amount of content covered in this course is:	TOO MUCH, TOO FAST	1 – 3 – 5 – 3 – 1	TOO LITTLE, TOO SLOW
Instructional materials and activities appear to be conscientiously prepared or chosen.	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
The opportunity for students to ask and answer questions of the instructor during class has been effective for improving understanding of material.	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
How beneficial are ***homework calculation problems*** for learning subject matter?	VERY BENEFICIAL	5 – 4 – 3 – 2 – 1	INEFFECTIVE
How beneficial are ***homework reading/multimedia questions*** for reinforcing concepts or learning about real-world applications?	VERY BENEFICIAL	5 – 4 – 3 – 2 – 1	INEFFECTIVE
The amount and difficulty of ***calculation/reading questions*** assigned by the instructor are:	EXCESSIVE	1 – 3 – 5 – 3 – 1	NOT ENOUGH
How well does the instructor coordinate the use of physical experiments, models, or demonstrations in the course?	VERY WELL	5 – 4 – 3 – 2 – 1	POORLY
The physical experiments, models, or demonstrations or models provided a valuable reference when completing in class assignments/assessments.	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
Hands-on experiments, models, or demonstrations were helpful in understanding structural dynamics concepts.	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
The use of smart phones in lab (ie. accelerometer application) made data collection more interesting and accessible to me.	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
Office hours and in-person/email instructor interaction has been effective to get my questions answered and better understand the materials	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
How effective was the instructor in preparing students for quizzes/exams?	VERY EFFECTIVE	5 – 4 – 3 – 2 – 1	INEFFECTIVE
Sufficient feedback is provided by the instructor/grader to clarify errors and make improvements one-on-one in person or in grading assignments	STRONGLY AGREE	5 – 4 – 3 – 2 – 1	STRONGLY DISAGREE
The grading of assignments and quizzes/exams is:	VERY FAIR	5 – 4 – 3 – 2 – 1	UNFAIR

Feedback on Specific Class Activities

Please circle the number on the scale which best represents your perceptions of specific class activities, where a ranking of 5 signifies "Effective/Interesting" and 1 signifies "Ineffective/Uninteresting":

SDOF Free Vibration – Collecting acceleration data for cantilevers of various materials/height	5 – 4 – 3 – 2 – 1
Damping – Collecting data with triangular, one-story model (sloshing/tuned-mass damper)	5 – 4 – 3 – 2 – 1
Forced Vibration – Conducting frequency sweep on cantilever models using shake table	5 – 4 – 3 – 2 – 1
Dynamic Amplification – Processing frequency sweep data to create an Rd curve	5 – 4 – 3 – 2 – 1
MDOF Diaphragm – Experimenting with a mass shaker on the diaphragm model	5 – 4 – 3 – 2 – 1
MDOF Mode Shapes – Testing 3 story portal frame models on shake table (*video)	5 – 4 – 3 – 2 – 1
MDOF Animations – Experimenting with MATLAB GUI to visualize mode shapes (*HW7)	5 – 4 – 3 – 2 – 1 or N/A

Comments: Please be as specific as possible.

A. What are the major strengths and weaknesses of the instructor with respect to teaching techniques/tools utilized in class, lab, office hours and email interactions (not homework/lab or assessment writing)? Indicate suggestions to improve weaknesses.

B. What aspects of this course have been most beneficial to you? (What is helping you learn? What is interesting? What would you have liked to do more of?)

C. What do you suggest to improve this course and the specific class activities listed in the previous section? (Do you want things done in class a different way? Are there modifications to existing activities or additional activities that might help you learn?)

D. What do you suggest to improve class/lab: (i) homework/lab assignments to maximize learning gains for your time investment and (ii) assessments (quizzes/exams) to best demonstrate your learned knowledge.

E. What did you think of the physical models, demonstrations, and/or experiments described in the previous section? (Do they aid you understanding, or not? Interesting? Engaging? Why?)

F. What are the major strengths and weaknesses of the physical models, demonstrations, and/or experiments that were used in this course? Indicate suggestions to improve weaknesses.

G. Over the course of this class, have you used social media (Snapchat, Instagram, Twitter, etc.) to share what you were working on in ARCE 412 or ARCE 354, or have you seen other students sharing pictures or videos of lab activities (shake table, collecting data with smart phone accelerometers, etc.)? How frequent was the use of social media?

D Physical Model Construction Plans

D.1 Cantilever Model

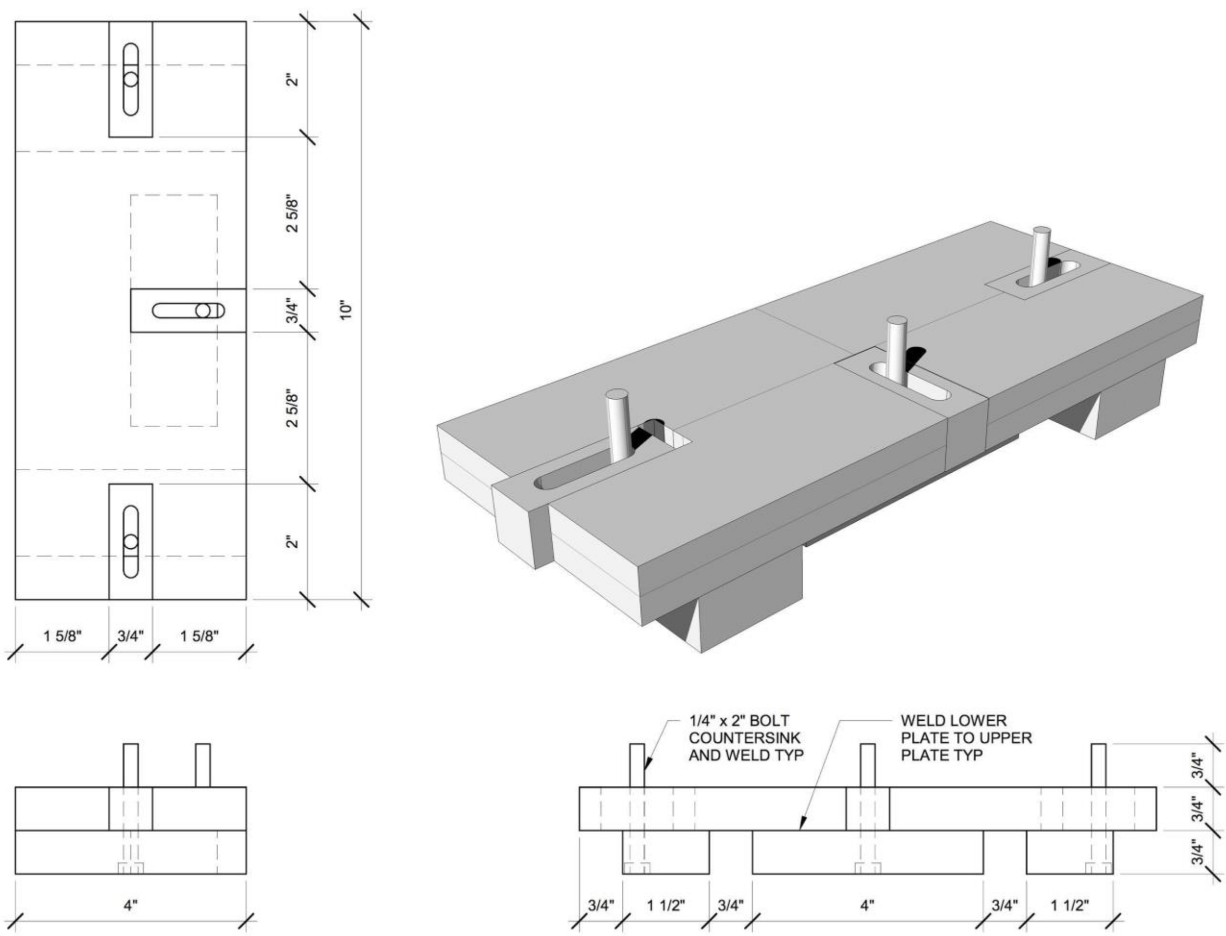


Figure D.1: Winter 2018 Steel Base Plate

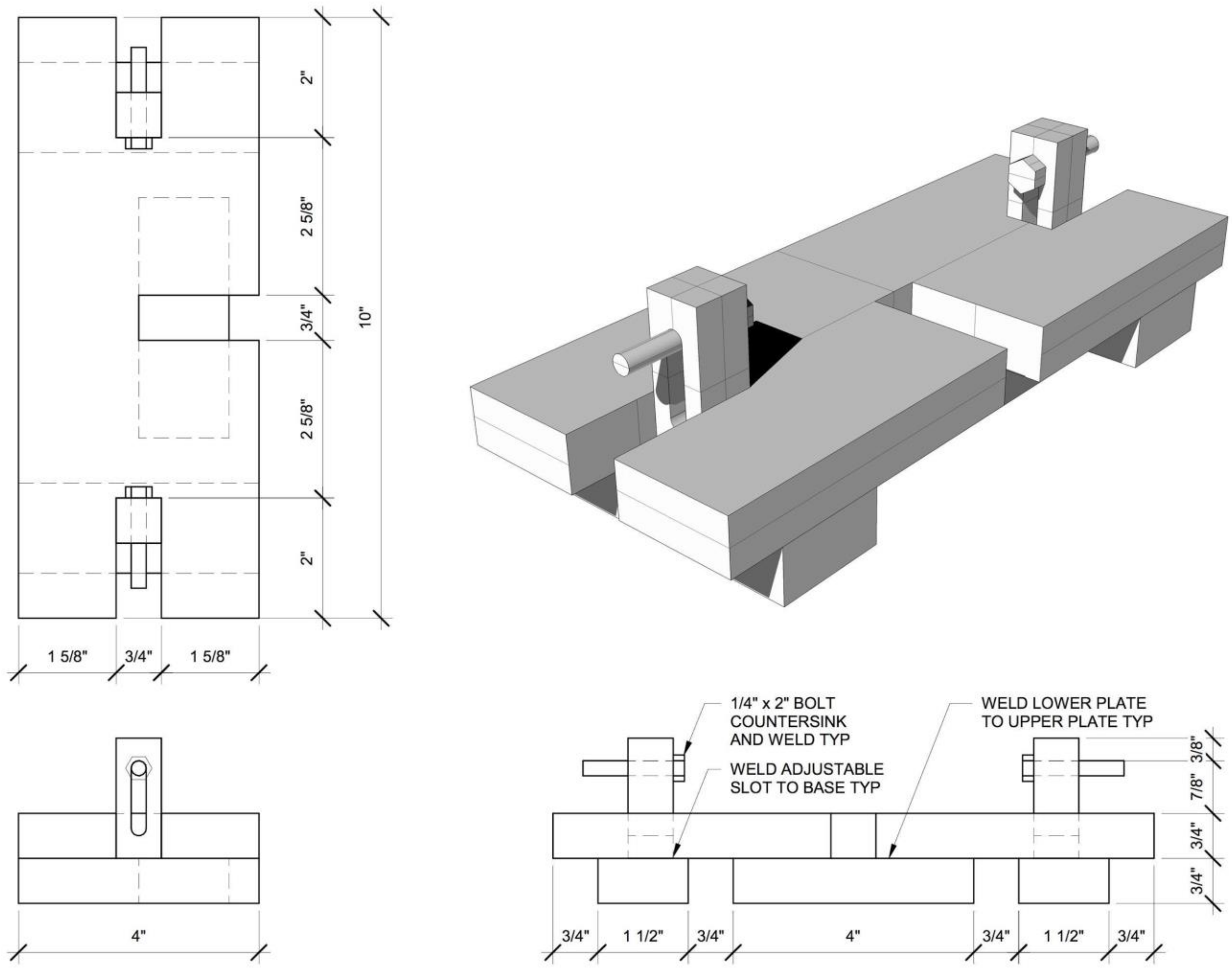


Figure D.2: Spring 2018 Steel Base Plate

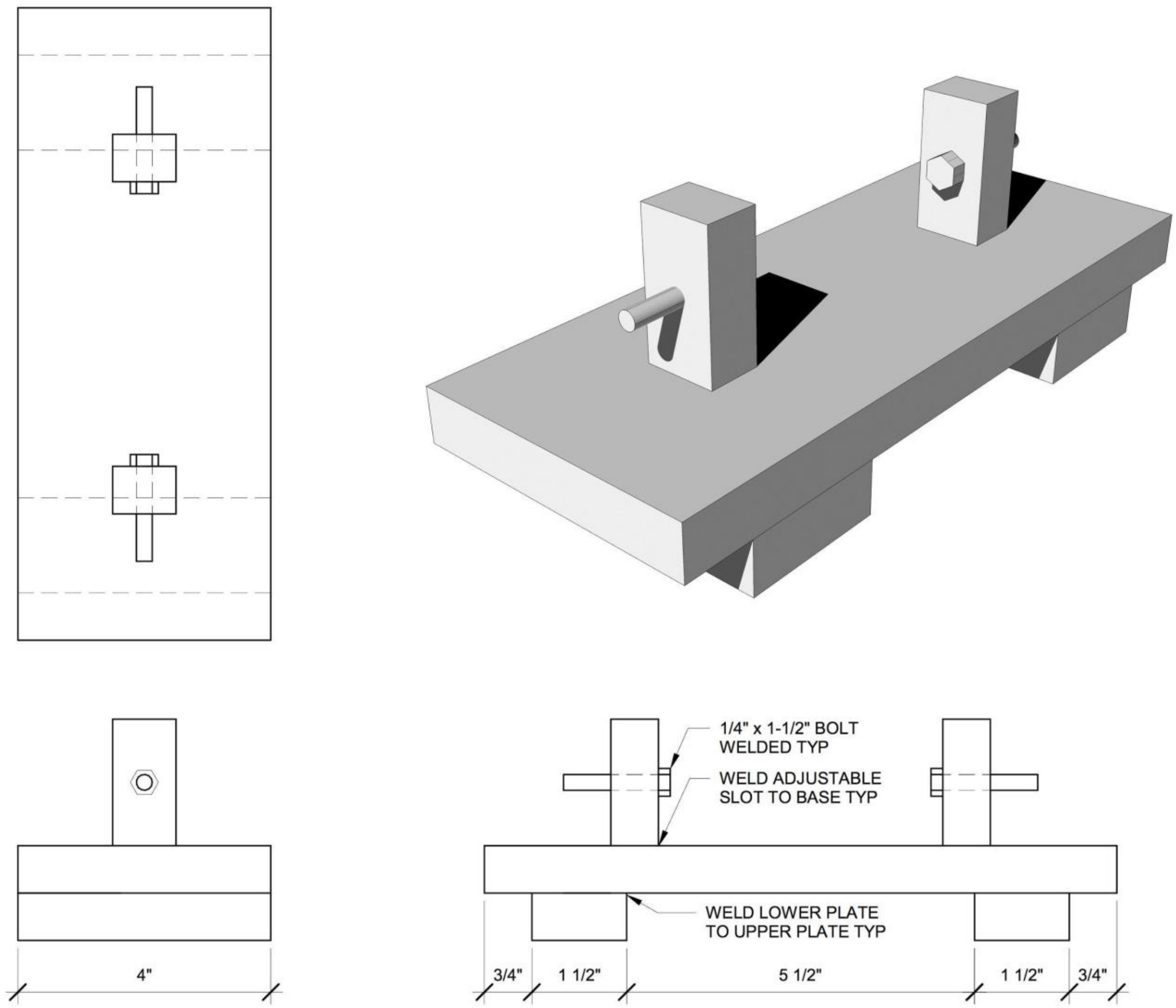


Figure D.3: Suggested Steel Base Plate Design

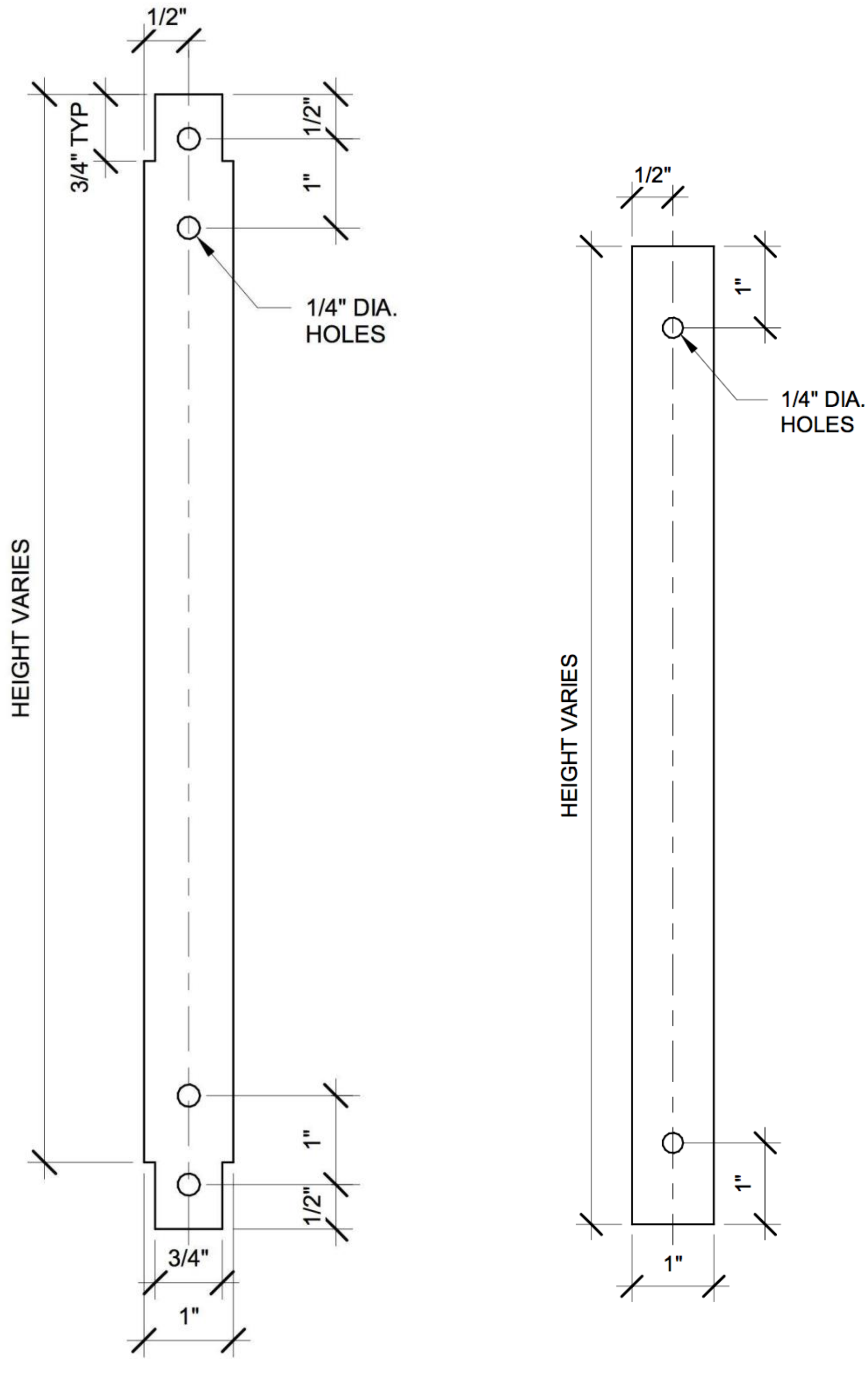


Figure D.4: Cantilever Specimen (left: W18, right: suggested)

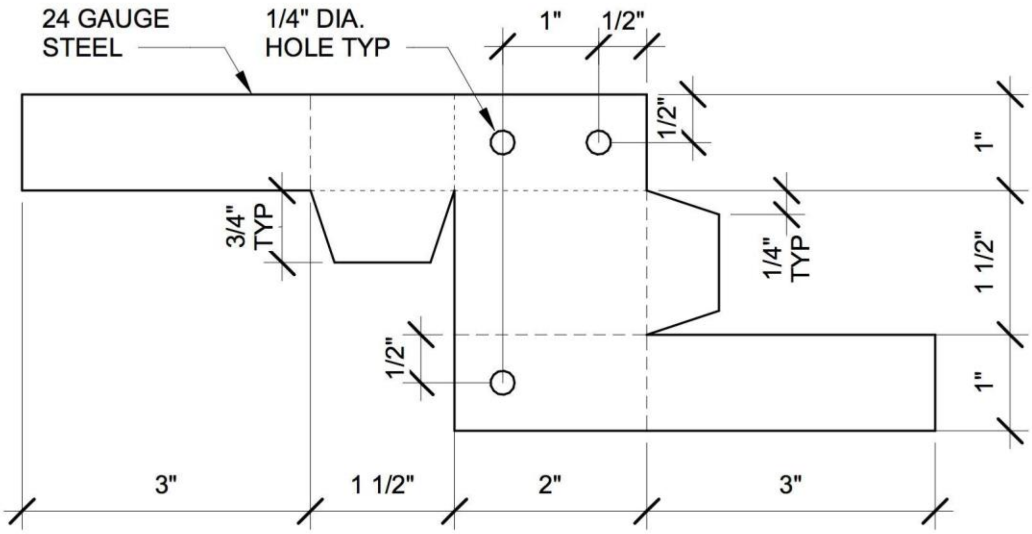


Figure D.5: Unfolded Phone Mount

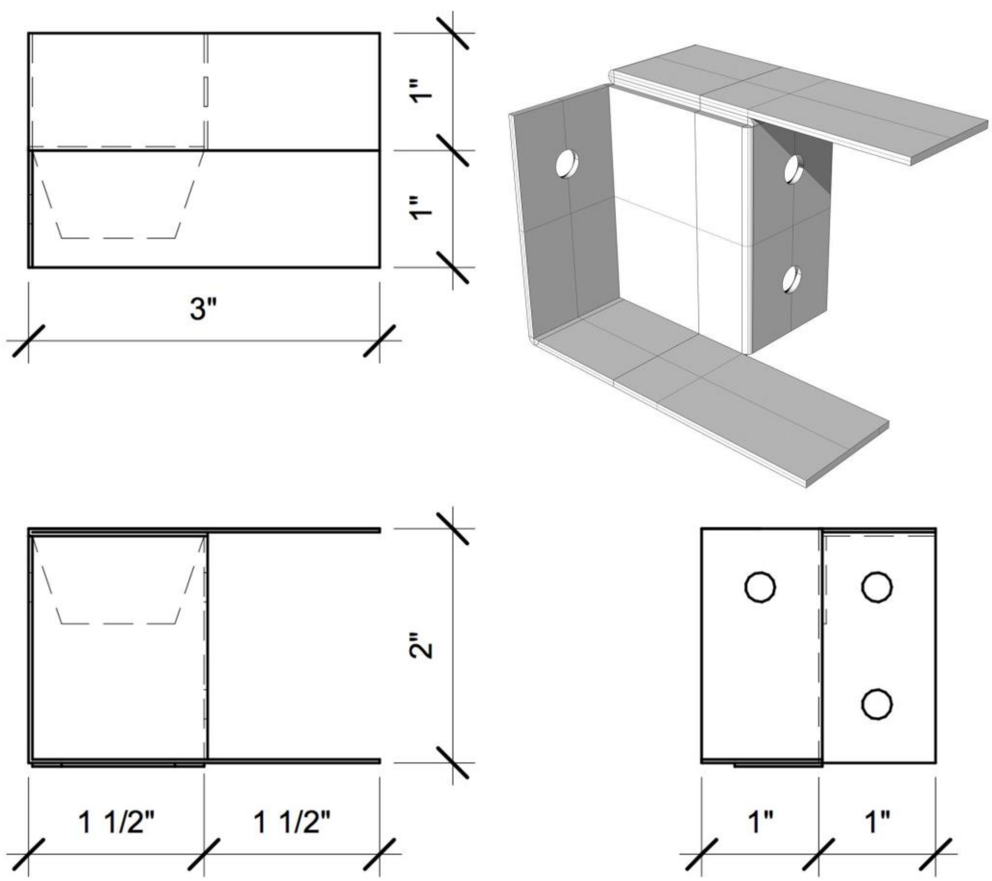


Figure D.6: Folded Phone Mount

D.2 Damping Attachment for Triangular Model

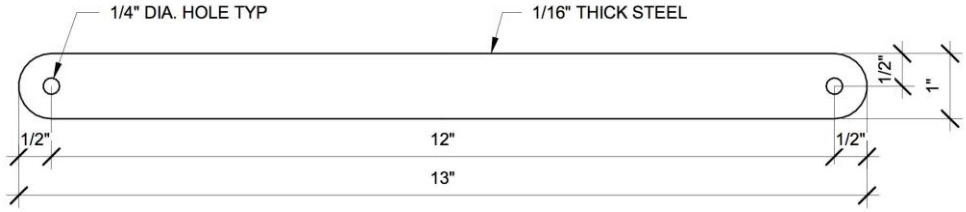


Figure D.7: Damping Attachment Top Bar - Upper

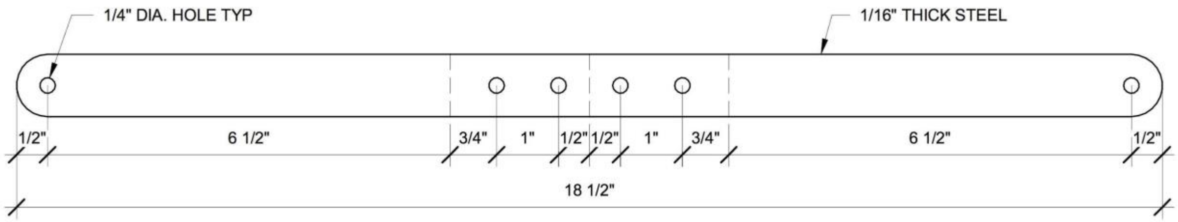


Figure D.8: Damping Attachment Top Bar - Lower

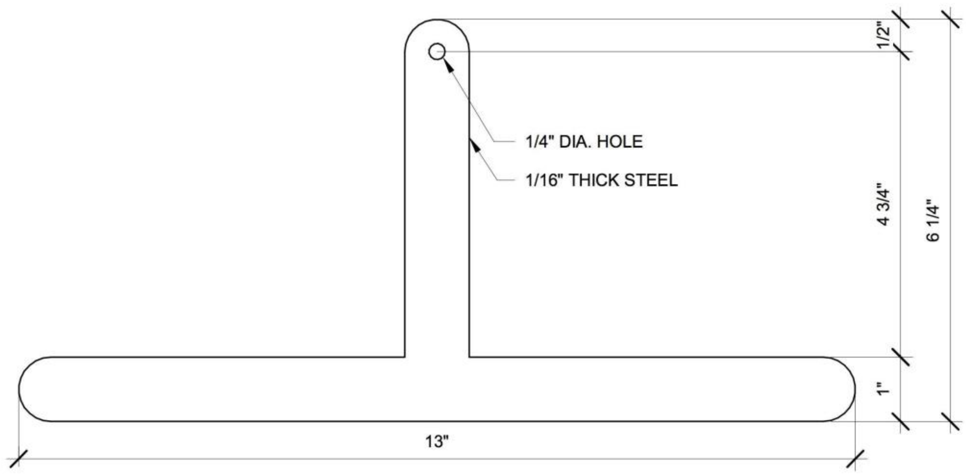


Figure D.9: Damping Attachment T-Bar

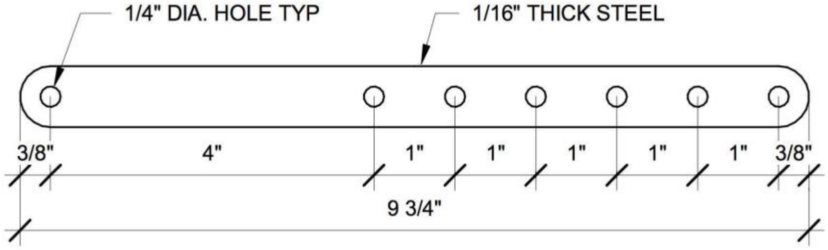


Figure D.10: Damping Attachment Pendulum Arm

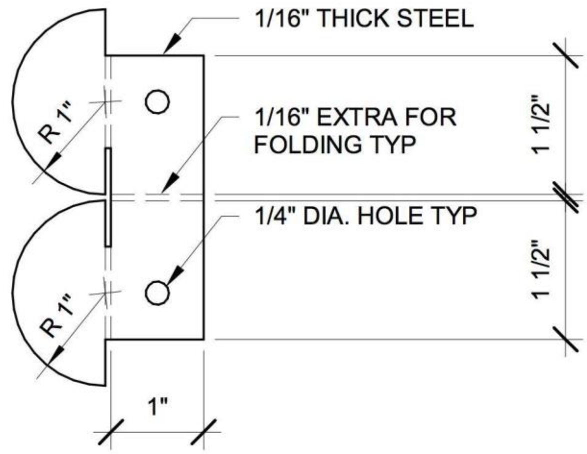


Figure D.11: Damping Attachment Seat for Weights

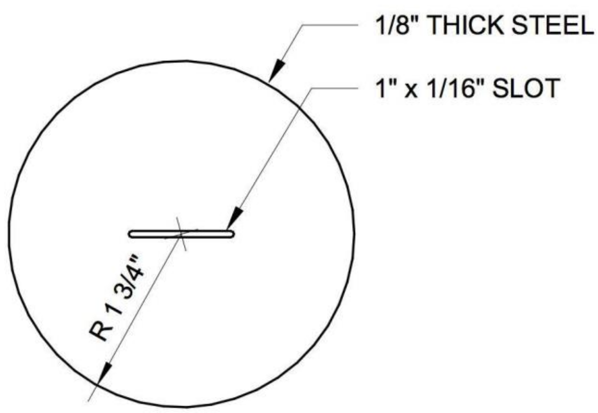


Figure D.12: Weight for Damping Attachment

Figure D.13: Damping Attachment Assembly

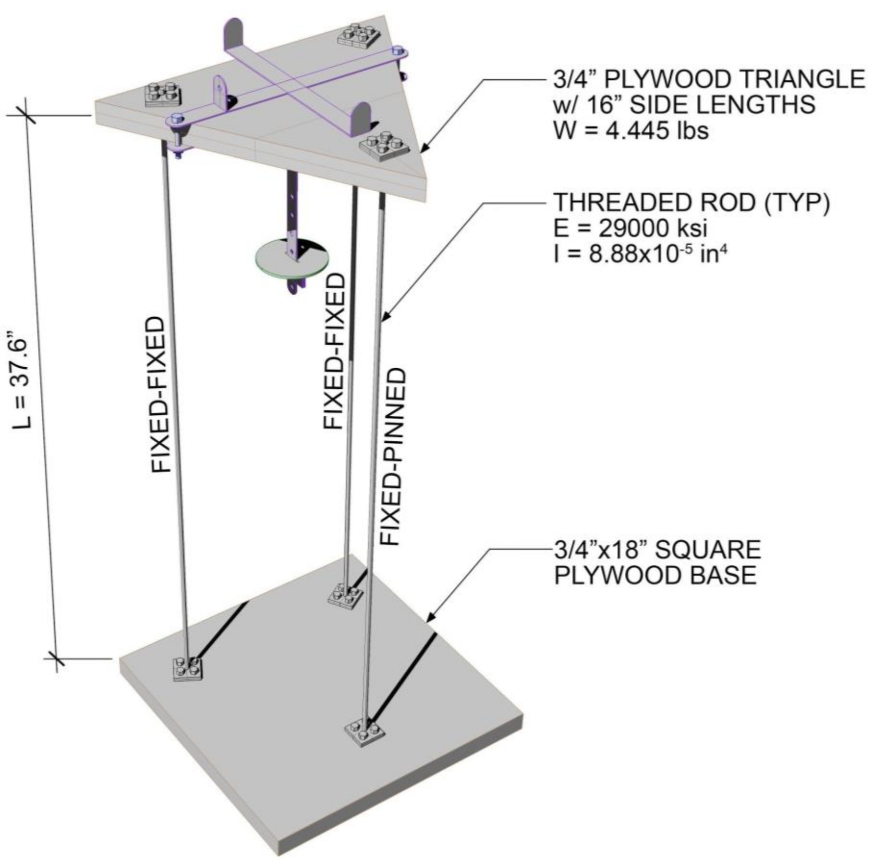


Figure D.14: Damping Attachment Secured to the Existing Triangular Model

D.3 Rigid Diaphragm Model

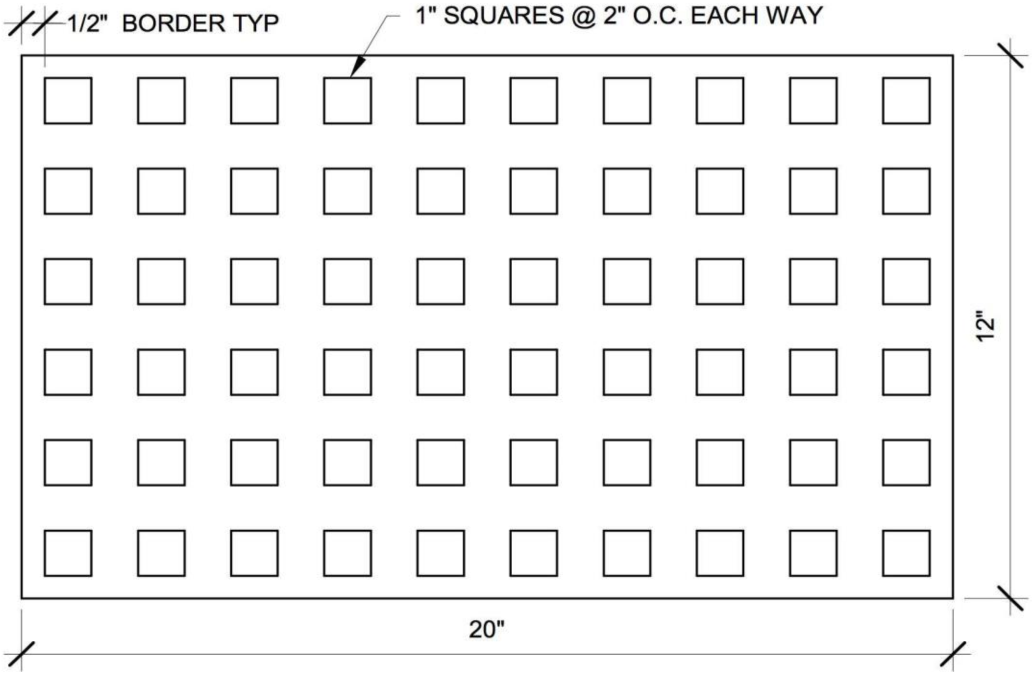


Figure D.15: Base (3/4" Wood) and Diaphragm (1/4" Plexiglass) Design

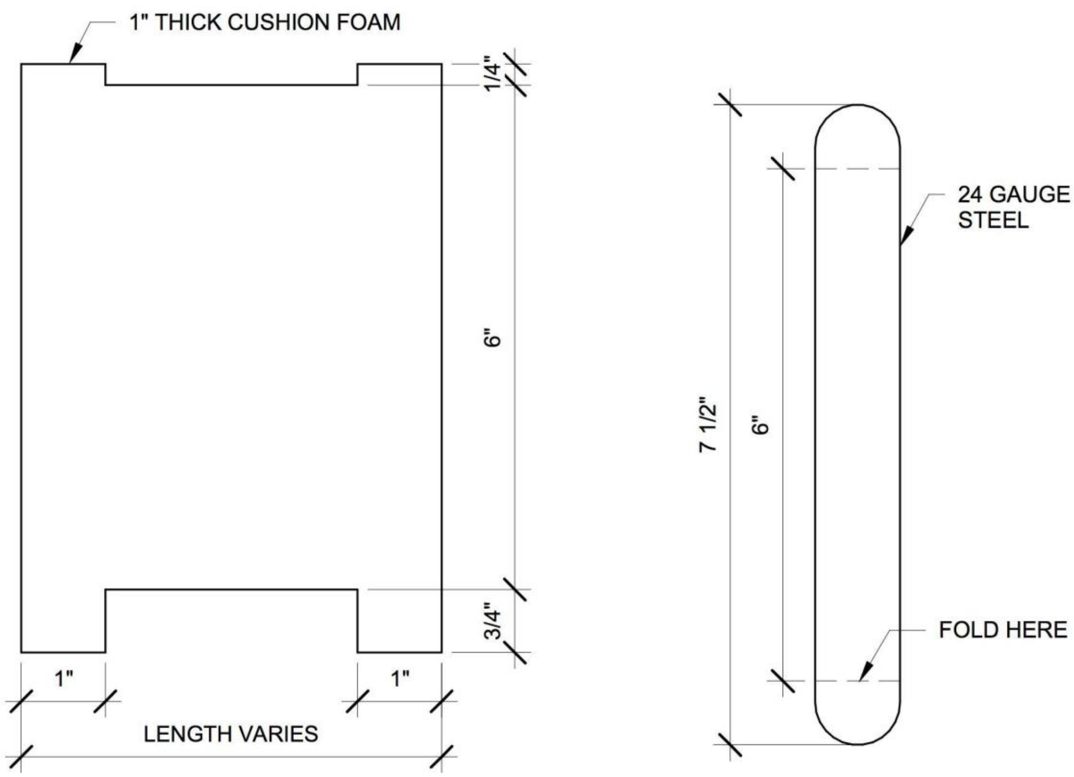


Figure D.16: Foam Wall Design (left) and Chord Design (right)

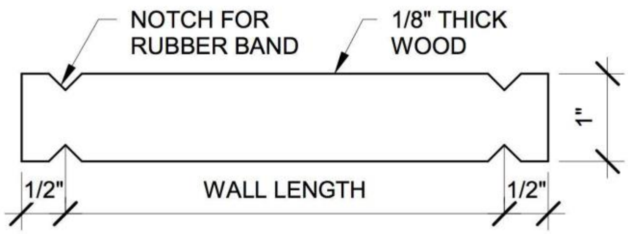


Figure D.17: Wood Anchor for Foam Shear Walls

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Figure D.18: Foam Shear Wall Assembly

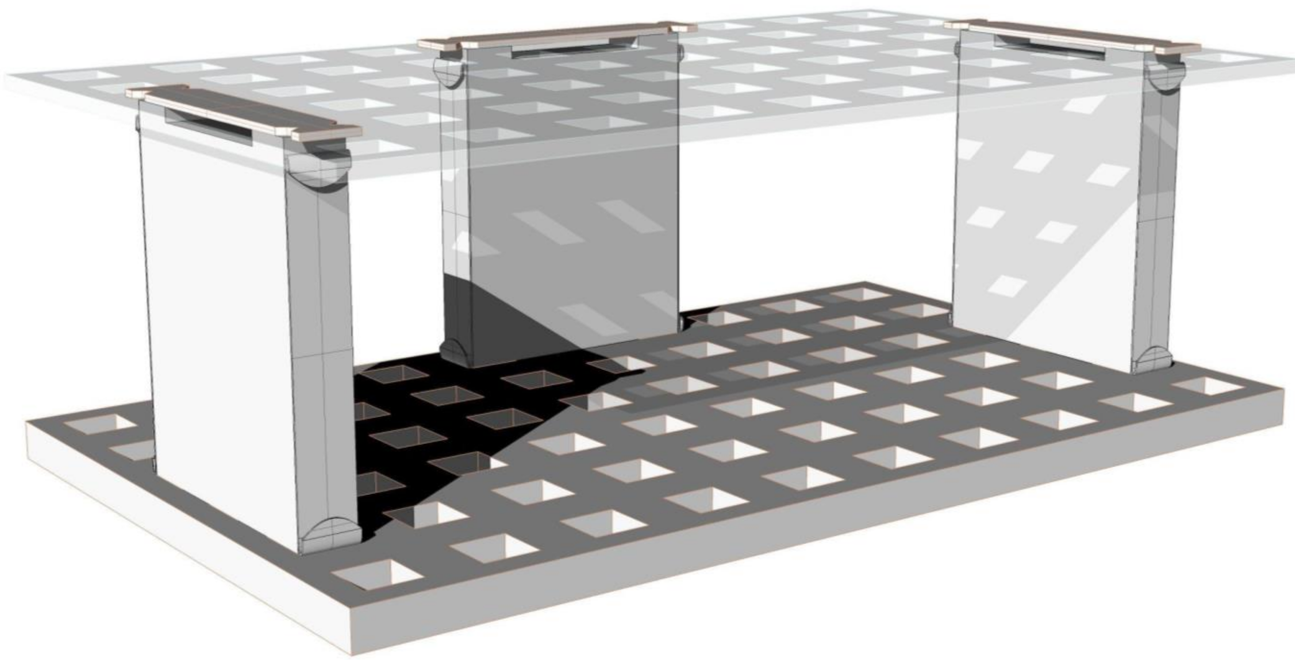

Figure D.19: Rigid Diaphragm Assembly

D.4 2-Story Portal Frame Model

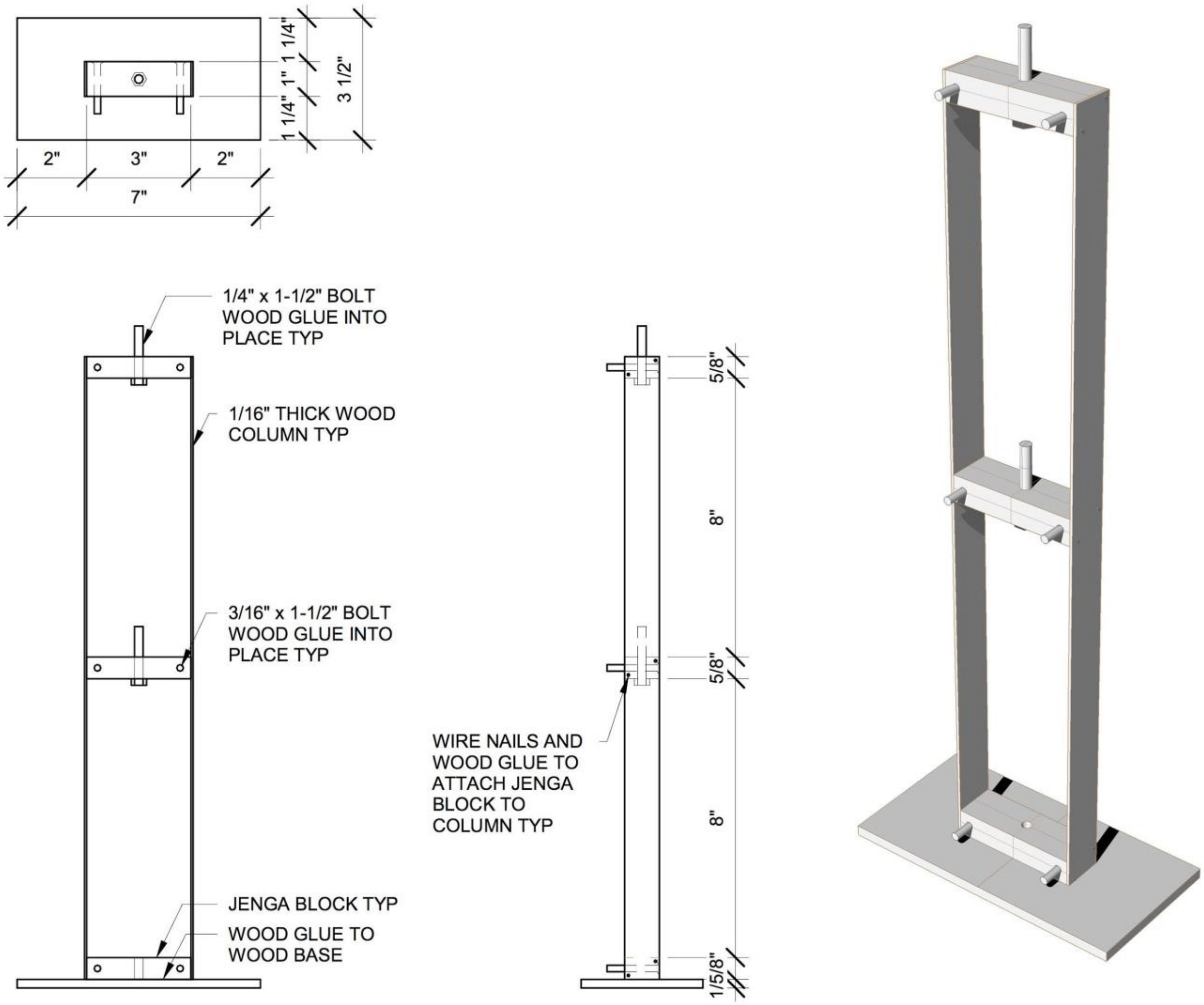

Figure D.20: 2-Story Portal Frame Design

E Human Studies Research (IRB) Submission Documents, Project # 2018-075-CP

E.1 IRB Manager Approval

CAL POLY
SAN LUIS OBISPO

Project

Project:	**2018-075**	**Sponsor(s):**	
Committee:	IRB	**Sponsor Id:**	
Category:	College of Architecture and Environmental Design	**Grants:**	
Department:	Architectural Engineering		
Agent Types:	Educational Intervention • Survey/Questionnaire	**CRO:**	
Title:	Use of Physical Experiments and Models in an Undergraduate Structural Dynamics Course	**Year:**	2018
Comments:			

Project-Site

Site(s):	**CP - Cal Poly State University, San Luis Obispo**	**PI:**	**Behrouzi, Anahid**
Status:	Active	**Additional:**	N
Approval:	March 5, 2018	**Expiration:**	**March 4, 2019**
Initial Approval:	March 5, 2018	**Other Expirations:**	
Level of Review:	Minimal		
Tags:	Expedited/Minimal Review		
Comments:			

Contacts (1)

Name	Role
Facciolo, Charles	Co-Investigator

Events (1)

Event	Att	FE	Instance/UDF	Start	Complete	Last Mtg
Initial Submission	4			03/01/2018	03/07/2018	

E.2 IRB Manager Paperwork

Available upon request.

E.3 IRB Manager Attachment - Research Protocol

Available upon request.

E.2 IRB Manager Attachment - Survey Instrument

Refer to survey included in Appendix C.

E.2 IRB Manager Attachment - Recruit and Consent

Available upon request.