

Characteristics of a Viscous Damper: Finding the Damping Coefficient

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By

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Abstract

The authors of this report are undergraduate Architectural Engineering students at California Polytechnic State University in San Luis Obispo. This report documents the implementation, design, and experimentation of a damper with unknown properties. This experimentation data was used to find the damping coefficient of a viscous damper alongside damping characteristics. Using knowledge from previous courses, this report focuses on dynamic responses through an assumed viscous damper. Through forced oscillatory motion testing with specified frequency and amplitude using the seismic shake table and equipment, compactDAQ instrumentation, and damper, values were determined from the data experimentation, which can be used to numerically or analytically derive a coefficient of damping.

Since the damper is initially assumed to be viscous, the damping coefficient may be found with the equation $F = CV^\alpha$, dividing force by velocity to derive the damping coefficient C is the damping constant, with units of lbs-sec/inch, V is the velocity in terms of in/sec, and α is the velocity exponent ranging from 0.3 to 1. The damping coefficient was derived analytically through comparisons of experimentally derived hysteretic curves. These reference curves were generated from an ETABS model of the damper, modeled as a link with similar properties. Due to the fact that the exact stiffness and damping of the experimental damper are unknown, those properties of the ETABS damper were iteratively input until hysteretic curves were developed that closely matched the experimentally derived ones. Once the inputted properties produced graphs that matched for a certain number of cases of differing frequency, displacement, and motion, the damping and stiffness of the real viscous damper were approximated.

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1. INTRODUCTION

This report analyzes and tests the characteristics of a damper. Through previous Cal Poly Architectural Engineering courses, the authors have a basic understanding of damper effects on the dynamic response of a building. The undergraduate program has an emphasis on structural dynamics and seismic analysis for building design and analysis. The concepts of damper analysis and design is a topic that is not taught in depth through undergraduate courses, so they will grasp a greater understanding of viscous dampers through the testing of this particular damper, as seen from **Figure 1.1**. The authors will utilize the shake table located in the department's seismic lab alongside other testing equipment to acquire experimental data. They will experiment with the shake table and compare with values taken from ETABS [2]. The results from the ETABS model will also be compared with the physical testing. The authors are currently undergraduate students in the Architectural Engineering department.

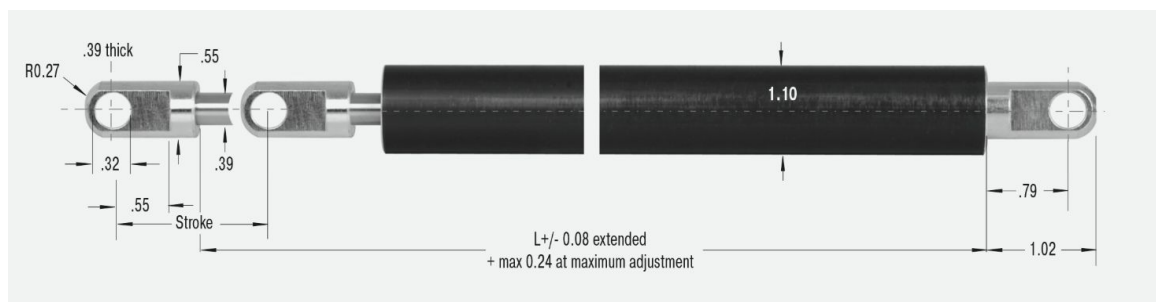


Figure 1.1 Image of specified damper with dimensions, from manufacturer website [4].

1.1. Research Motivation

Damping is a facet of earthquake engineering that nearly all engineering students are exposed to in some capacity during their education, and in some cases, professional career. In undergraduate education, damping is not covered as thoroughly. Usually, when damping is discussed in detail, it is concerned with uses in seismic design and analysis, through its various mechanical forms, as well as its effects on the dynamic response of structures when applied.

These particular dampers were used for a previous senior project, in particular the Reefa Structural Identification: Computer Analysis of 3-Story Frame by Jennifer Briggs, for an experimental building demonstration model found in the seismic lab. The Reefa structure was built by Blake Reeve and Brianna Kufa, as seen in **Figure 1.1.1**. In addition, two

Architectural Engineering graduate students, Karen Freda and Carla Simental, analyzed and experimented on the Reefa Structure. The data and analysis from this report will supplement this model and previous projects for future testing and experimentation. Currently, it would be difficult to predict a structure's behavior while using this particular damper because the manufacturer does not specify any properties of the damper besides its dimensions. Finding the damping coefficient of this particular damper would make using it in future projects much easier and allow for better predictions of behavior.

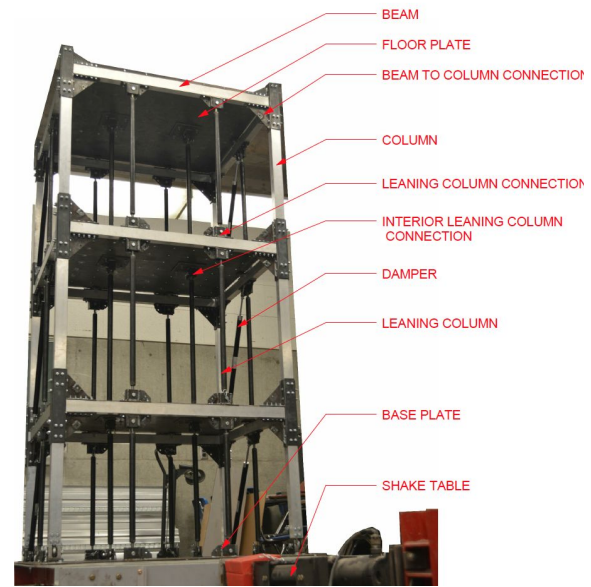
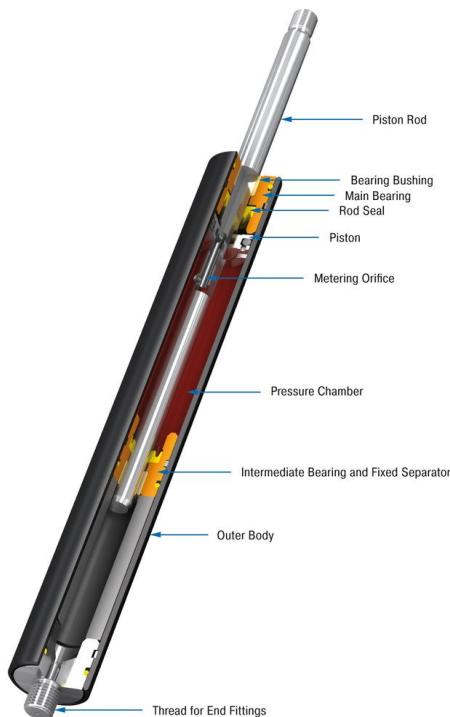


Figure 1.1.1 REEFA 3-Story Structure [9]

1.2. Viscous Dampers: Related Work



This report will also determine whether the damper tested is truly a viscous damper. Through plotting the hysteretic curves after test runs, it will become easier to tell if it will be viscous or not. Fluid Viscous dampers have originally been used as shock absorbers for the defense and aerospace industries [6]. In recent years, dampers have been used for seismic applications for new and retrofit construction [6]. They are often seen in buildings near faults for earthquake protection. They are also commonly installed combined with steel or reinforced concrete special moment resisting frames for building design in high seismic regions [5]. This resulting design will create a highly damped, low-frequency building which limits seismic demand on structural and non structural components [6]. Dampers may increase initial expenses but they significantly improve seismic performance and life cycle cost.

Figure 1.2.1 Section Cut of Specified Damper [3]

Viscous dampers are velocity-dependent mechanisms that are oftentimes used to dissipate energy. They are pistons with a type of viscous fluid that, when compressed or extended, force fluid through an opening into another chamber, which dissipates energy. Viscous dampers are made up of a piston immersed in a highly viscous fluid that moves in different directions. Damping forces form through shearing action and displacement in the fluid [5]. There are two main dynamic characteristics to focus on: the viscous fluid and geometry of the device. The fluid in a viscous damper can either be temperature-dependent or temperature-independent, depending on the required operating temperature of a system [5]. The geometry of viscous damper is an important factor in regards to how the size of the opening that the fluid flows through affects the speed of flow of the fluid, and thus the damping of the damper [10].

In this report, the tests will be placed with a load cell mounted on the damper to measure the reaction force. As similar through the NCCER report, *Section 2.3* has a model of viscous dampers in horizontal motion similar to this setup. A recorded force-displacement loop should display an elliptical shape for frequencies of motion up to 1 Hz, showing properties typical of a viscous damper [5]. Higher frequencies will show a basic elliptical shape but at a higher harmonic superimposed function. At max displacement, viscous dampers are at zero forces. At max forces, the viscous dampers are at zero displacement, as noted in recorded force-displacement loops.

2. EXPERIMENTAL SETUP

1. Attach damper to shake table and set to a forcing frequency (known forcing function).
 - a. Record response of the forces (lbs), displacement (in), and acceleration (g) via LabView[8].
2. Analyze recorded responses from exported Excel file to plot hysteretic curves.
3. Model damper in ETABS, initially inputting a trial value for the damping coefficient, and run sine waves through it.
4. Analyze curves and compare to ETABS hysteretic curves, changing the ETABS damping coefficient until they match.
5. Calculate average damping coefficient and analyze potential differences in values between different frequencies.
6. Results of the experiment will be validated through experimental and analysis of results.

3. SHAKE TABLE SETUP

3.1. Initial Setup

The apparatus used to test the damper has to be fashioned using the existing shake table in the seismic lab, located in the basement of building 21 at the Cal Poly campus in San Luis Obispo and shown in **Figure 3.1.1**. The damper is to be attached on one end to an angled base plate anchored into the floor with three 3/4" bolts. The other end, which will include a load cell, will be attached to an angle fastened onto the shake table with 3/4" bolts. The angle will be fitted with a plate that has been specially fashioned to hold the ball knobbed end. The ball knobbed end and the pinned end will make it so that the damper will have pinned connections on both ends, leaving rotation free if the motion of the shake table induces it. **Figure 3.1.2** and **Figure 3.1.3** show the equipment that are being used. **Figure 3.1.4** show the initial setup the students use before making changes.



Figure 3.1.1 The shake table in the seismic lab.



Figure 3.1.2 The angled base plate that holds one end of the damper through a pinned connection, anchored into the floor slab with 3/4" bolts.

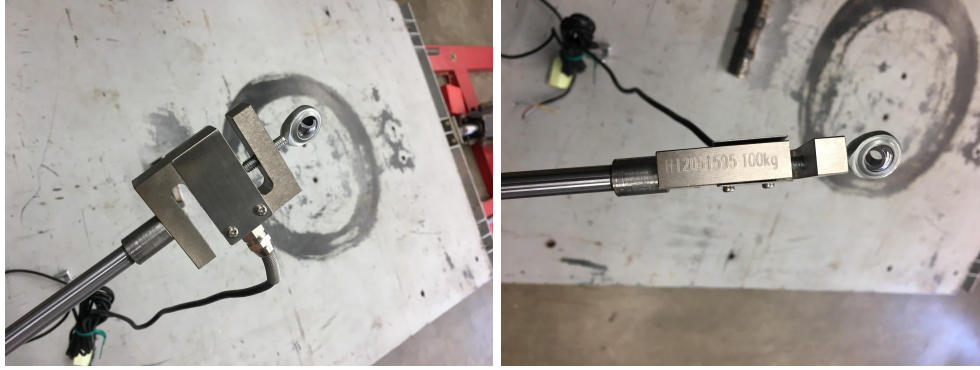


Figure 3.1.3 The load cell attached to the damper and pinned connection to angle on seismic table.

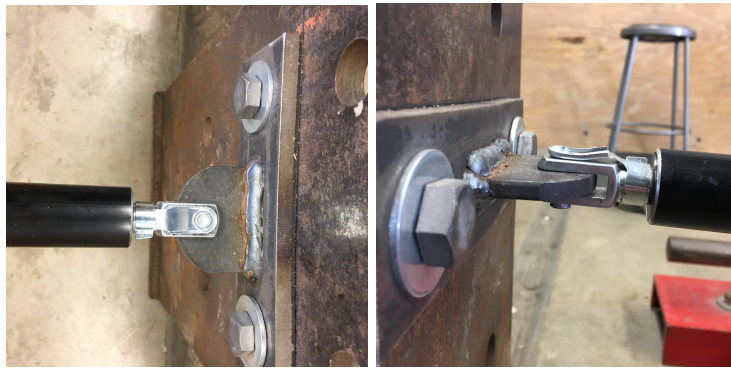


Figure 3.1.4 Detailed image of initial placement pinned connection of damper to angled base plate.

3.2. Final Setup



Figure 3.2.1 Detailed image of placement of pinned connection of damper to angled base plate.



Figure 3.2.2 Detailed image of placement of pinned connection of damper to angled base plate with inserted tools.

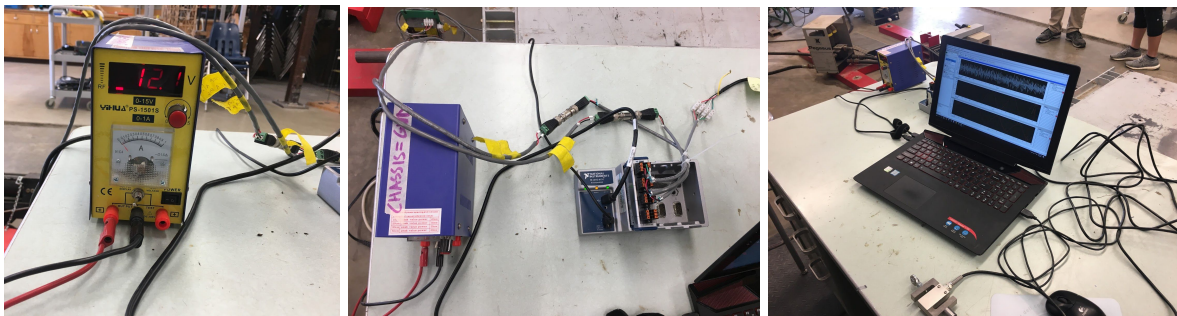


Figure 3.2.3 The connected configuration of voltmeter at 12V with the computer and CompactDAQ instrument.

Upon the actual setup of the damper, it was noticed that the damper's initial position was lengthened more than expected, to around 6". Considering that the damper has a total stroke of 8", this amount of extra extension was concerning. By running a sine wave with enough displacement, this could potentially over-extend the damper and cause the damper damage. Also, even if the displacement was not enough to cause damage, the damper would still be oscillated with its starting position near the end of its stroke. In doing so, it would not be accurate to run the damper through the shake table, assuming that a range of motion within range of the center of the damper's stroke is most desirable for oscillation. In **Figures 3.2.1 and 3.2.3**, the new setup to accommodate the damper at midway length is shown. The students added ten spacers to each bolt so it would add 4 inches. In addition, to account for the pullback and twisting after running the sine curve through the damper, aluminum foil was wrapped around the screw in the pinned connection to make it fit more snugly. In addition, tools were inserted to prevent additional pullback and twisting when the sine curve is ran, as shown in **Figure 3.2.2**. This was the final setup for the experiment before multiple testings.

3.3. LabView Instrumentation

To gather measurements and data for the force, displacement, and acceleration of the damper while being excited by the shake table, the authors used a program called LabView Signalexpress. LabView uses voltage measurements from strain gages in the load cell, a displacement transducer attached to the shake table, and an accelerometer within the shake table, all in units of mVpp/Vpp.

In LabView, the authors changed the properties to accommodate this experimentation. To measure the forces in the damper, a 100 kg load cell was used, which was called LC100kg. This was displayed in **Figure 3.3.1** alongside the samples read at the given rate in Hz needed for this experimentation. With assistance from Professor Peter Laursen, the load cell was calibrated to 74300 for the slope of the DAQ assistant, as seen in **Figure 3.3.2**. The value of 74,300 was derived by Laursen as the conversion factor for the strain gage within the load cell that converts mVpp/Vpp to lbs.

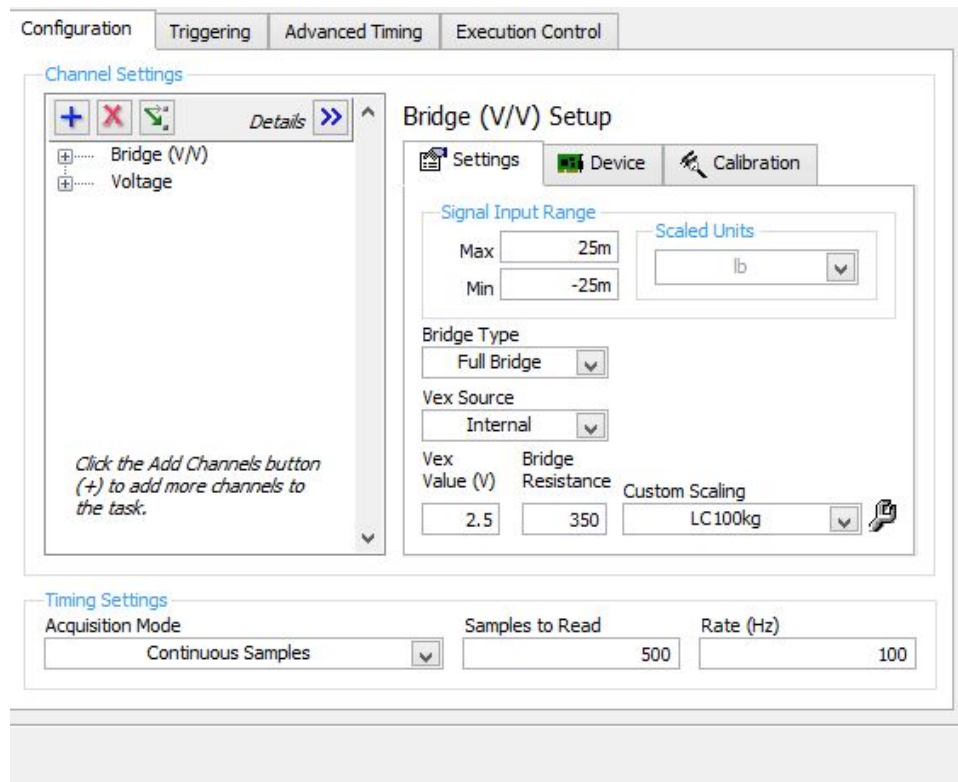


Figure 3.3.1 Labview Program: Step Setup Properties

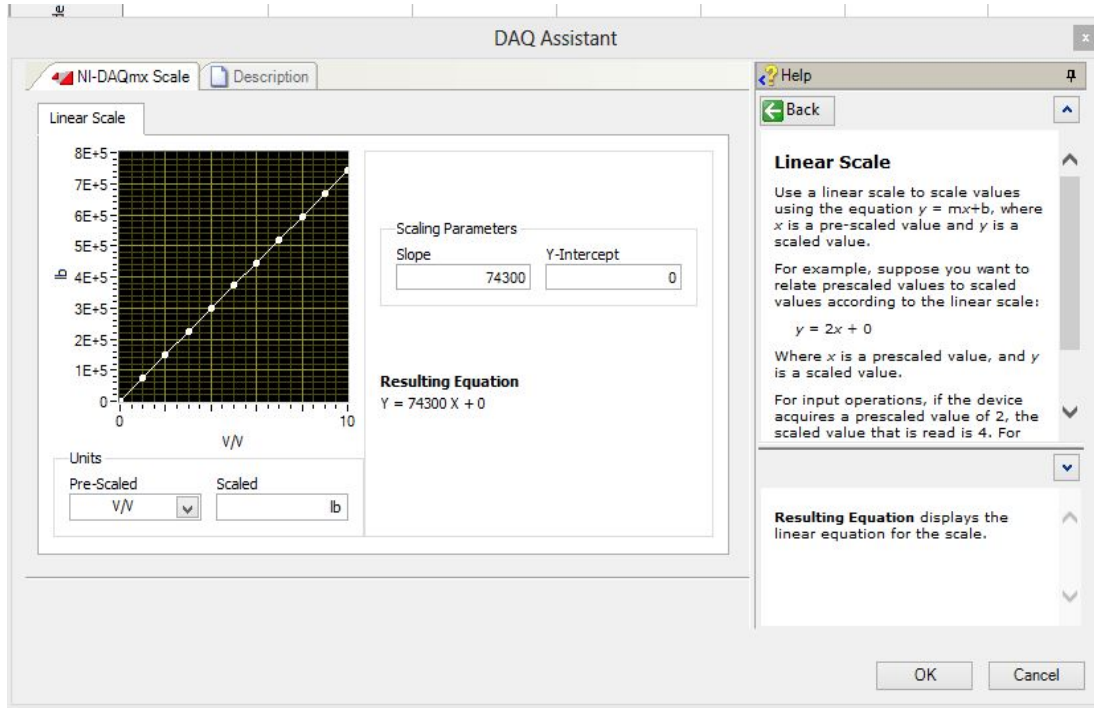


Figure 3.3.2 LabView Program: Custom Scaling (Wrench Symbol)

4. TESTING

Using LabView, the authors ran a sine curve with the initial setup seen in **Figure 3.2.1** and **Figure 3.2.2** before noticing minor problems. An initial load cell calibration value is given from Peter Laursen and checked by the authors for accuracy through the method of adding weights, as seen in **Figure 4.1**. Connecting it to the LabView program, the authors are able to determine the accuracy of the load cell as the values of the force curve jumps to the added weight value. The calibrated load cell value is used to set up in the program and connected to a voltmeter and compactDAQ instrument. In addition, the authors set up displacement, acceleration, and the load cell to its respective channels as it collected data from the shake table. The data collected would be shown on the laptop and ready to be exported in Excel.



Figure 4.1 Load Cell Testing

After exporting the results to Excel, a hysteric curve was plotted to look at the force vs. displacement of the damper at certain increments. LabView plots filtered and unfiltered data for the program. Filtered data filter out small frequencies under a certain value, which can be edited manually. It also zeros out the values so the students do not have an offset graph; the graph shown would then be at zero/origin.

Upon plotting the curves for motions up to 5 Hz as seen in **Figure 4.2** the hysteric curve is not as elliptical in nature. As the students start at 2 Hz and increased by 0.5 Hz increments until 5 Hz, it is noticed that the hysteric curves start forming an elliptical form at higher deformations. See *Section 1.2* for further background information. For frequencies of 5 Hz and above, the filtered and unfiltered data started to appear more elliptical in nature when plotted in Excel, showing that the damper is viscous. **Figure 4.3** shows the beginning of an elliptical hysteric curve.

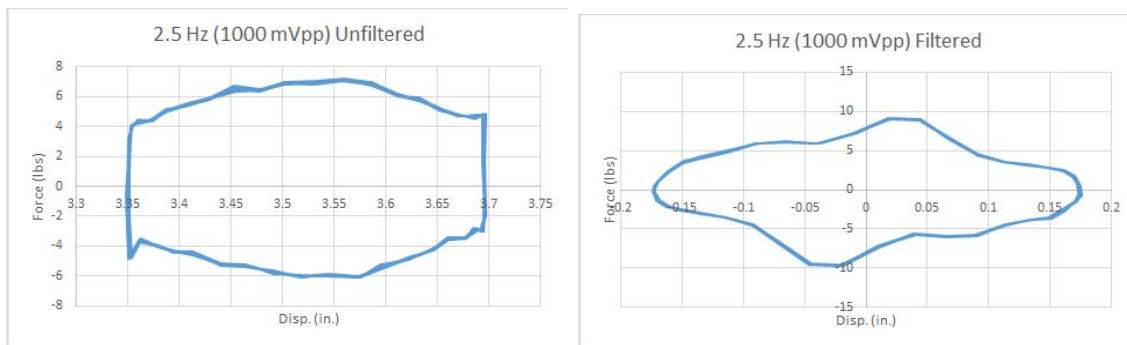


Figure 4.2 Hysteric Curve at 2.5 Hz and 1000 mVpp for filtered and unfiltered data.



Figure 4.3 Hysteric Curve at 4 Hz and 1000 mVpp for filtered and unfiltered data.

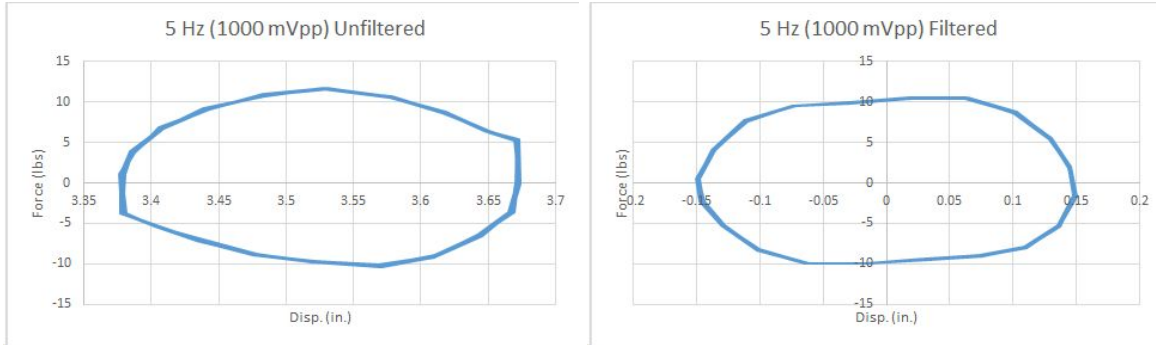


Figure 4.4 Hysteretic Curve at 5 Hz and 1000 mVpp for filtered and unfiltered data.

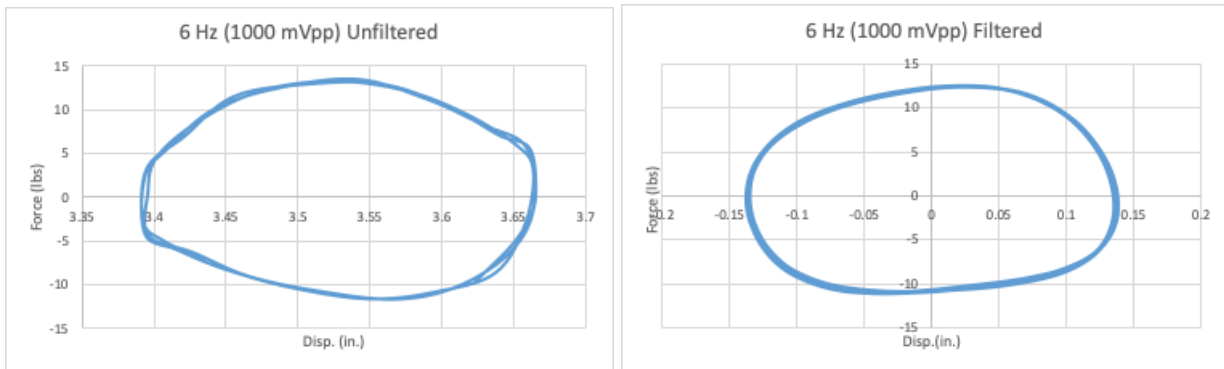


Figure 4.5 Hysteretic Curve at 6 Hz and 1000 mVpp for filtered and unfiltered data.

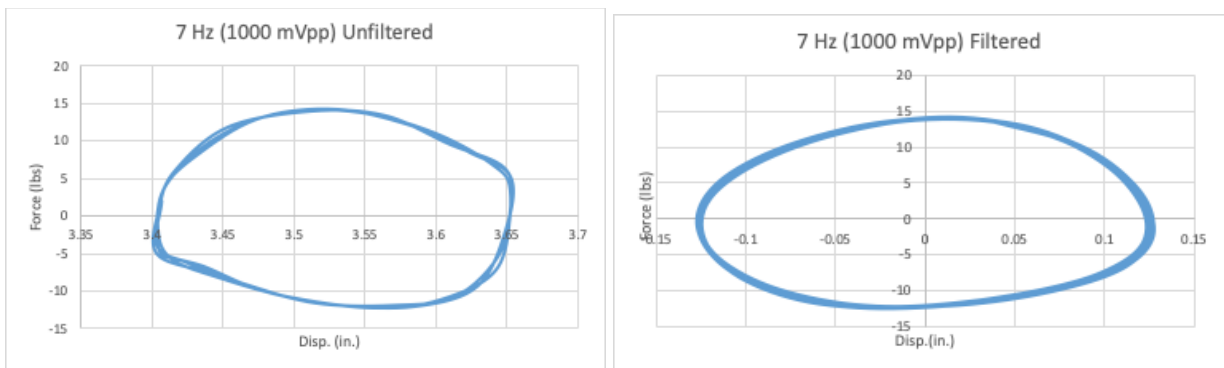


Figure 4.6 Hysteretic Curve at 7 Hz and 1000 mVpp for filtered and unfiltered data.

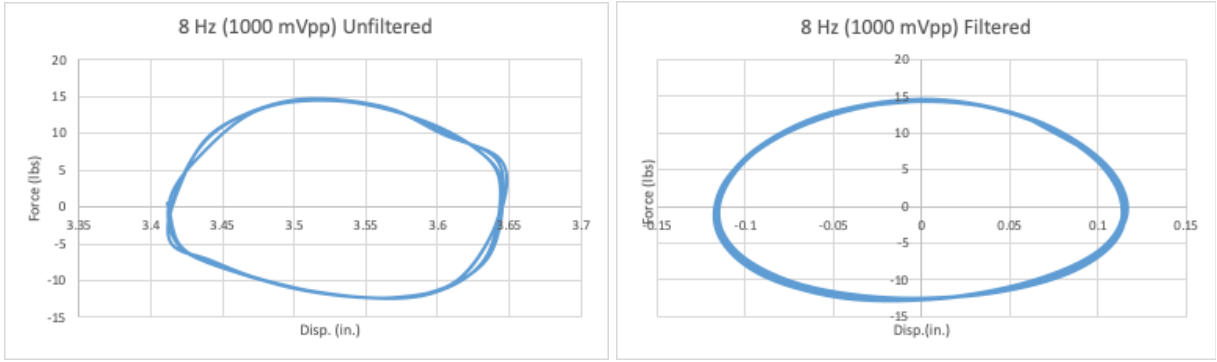


Figure 4.7 Hysteretic Curve at 8 Hz and 1000 mVpp for filtered and unfiltered data.

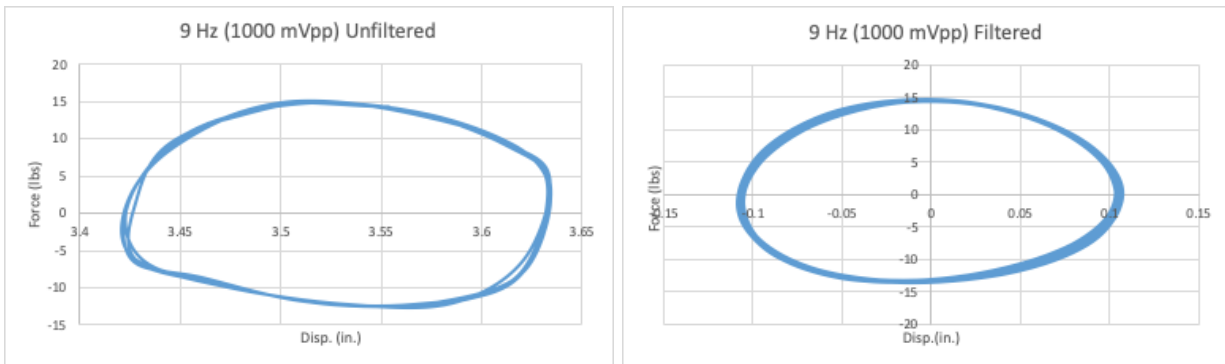


Figure 4.8 Hysteretic Curve at 9 Hz and 1000 mVpp for filtered and unfiltered data.

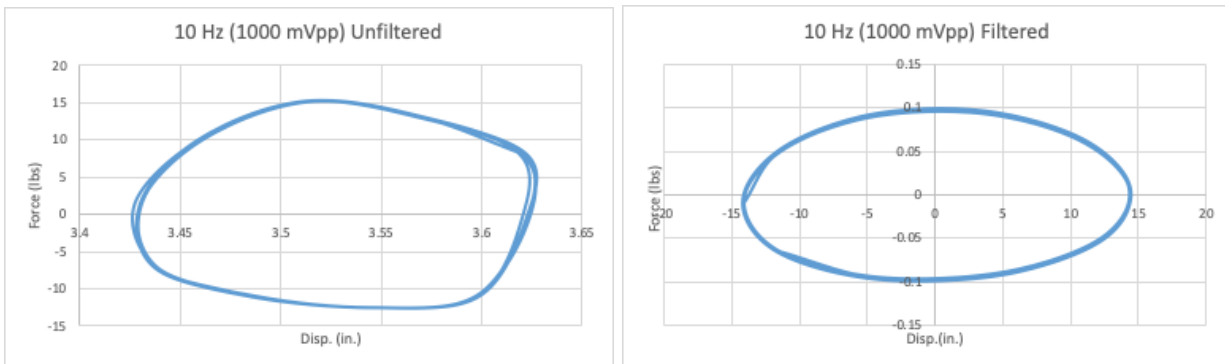


Figure 4.9 Hysteretic Curve at 10 Hz and 1000 mVpp for filtered and unfiltered data

One thing to observe between the sets of unfiltered and filtered data is that the unfiltered curves have noticeable irregularities that make them stand apart from the nearly-perfect ellipses of the filtered data. It was postulated that these irregularities were the result of certain voltage readings from the instrumentation equipment that came from sources such as ambient noise or vibrations, nearby electrical equipment, etc. It was decided that the filtered data was more accurate since it does not include the readings from these possible sources, due to LabView filters.

5. ETABS Model

5.1. Setup

Before initial testing of the experiment, the authors modeled a schematic, analytical model of the damper through ETABS. Material properties were unknown and adjusted after sine waves are run through the program and after experimental testing. The following graphic steps document the process of setting up the damper for analysis under a 5 Hz time history function, as was actually conducted for the project. First step is to set up a simple grid system for the damper. Then, a link is inputted through ETABS. The link element will have specific properties noted via **Figure 5.1.2** for a specific link type. For a viscous damper, the link will be “Damper-Exponential.”

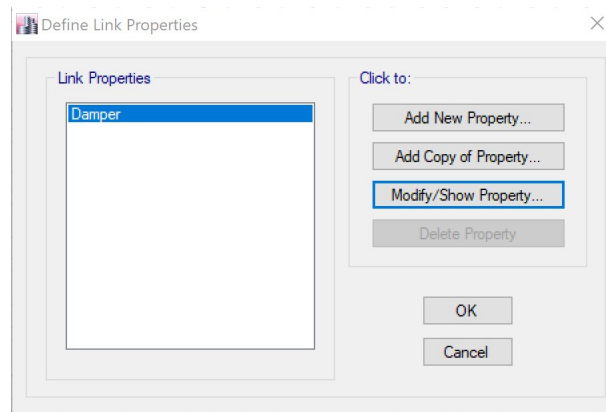


Figure 5.1.1 Link Property Data [Assign->Link-> Link Properties-> Damper->Modify/Show Property]

It is noted that this experiment assumes the link itself will be massless and the factors to be 1. The directional properties are noted and specified in the U1, x-direction, as it is based on its link direction. For this model, the U1 direction refers to the axial movement running along the damper’s length. The nonlinear property is checked for ETABS. The effective stiffness and damping is also inputted. Modify/show property for the specific direction is clicked to change the input values for the Linear Properties and Nonlinear Properties, as seen in **Figure 5.1.2**.

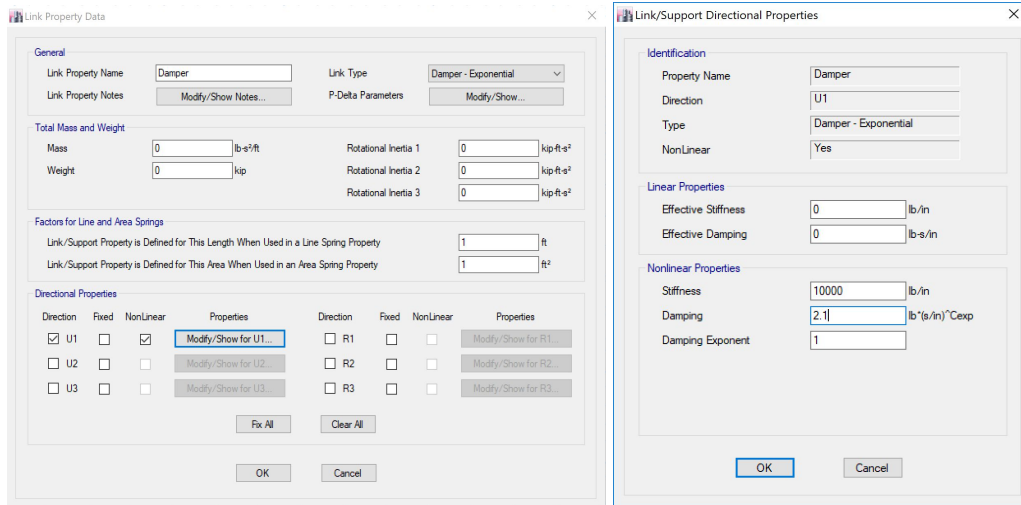


Figure 5.1.2 Modify/Show properties for damper.

Once the damper is set up, the students need to define the function properties for Time History Analysis. In Time History, a new function is added and the parameters are adjusted accordingly. Refer to **Figure 5.1.3** shows the parameters used for this experiment. The ETABS model will have differing load cases based on the tested ground motion for the time history analysis.

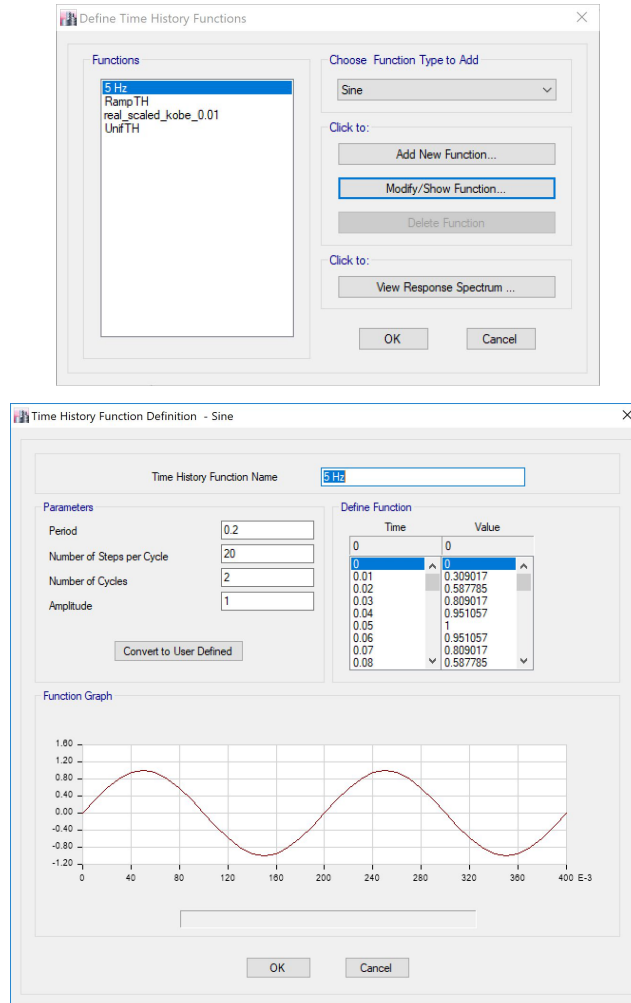


Figure 5.1.3 [Define->Function->Time History -> Modify/Show Function]

In order for the damper to experience excitation, a new load pattern must be added for seismic forces. To do this, just add a seismic pattern with self-weight factor of 0, as seen in **Figure 5.1.4**. In the Load cases, a new load case is added and modified for the data, as seen in **Figure 5.1.5**.

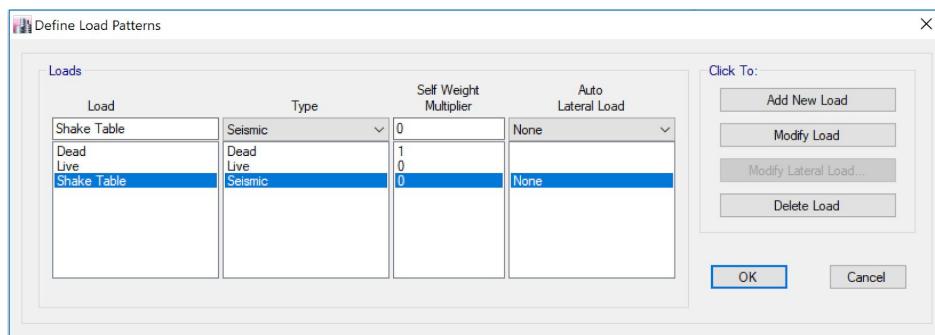


Figure 5.1.4 [Define -> Load Patterns -> Type = Seismic -> Add New Load]

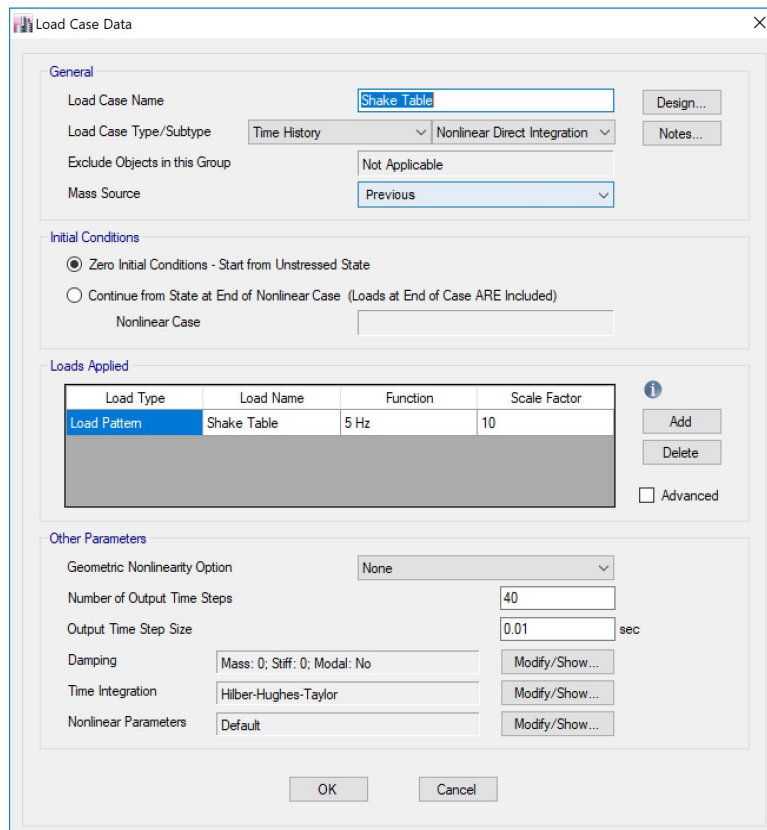
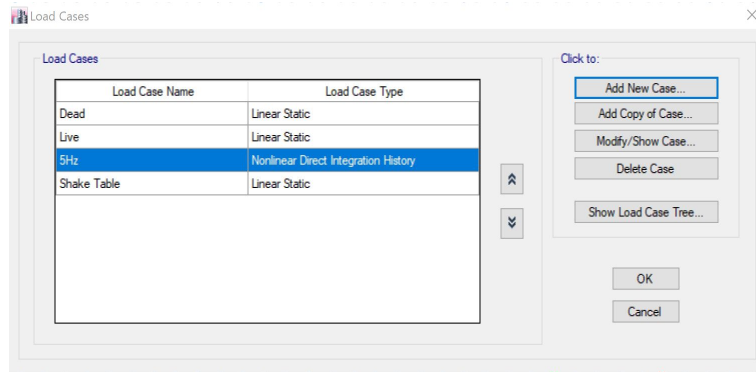


Figure 5.1.5 [Define -> Load Cases -> Add New Case]

Important to Note:

In the section of the Load Case Data Box in **Figure 5.1.5** called “Other Parameters”, the two inputs labeled “Number of Output Time Steps” and “Output Time Step Size” are vitally important to the results of the analysis, specifically how the hysteretic curve plots. The “Output Time Step Size” input dictates at what time step (in seconds) the load case outputs a value during analysis, and the value of the time step in this box must match the time step of the time history function that was generated in **Figure 5.1.3**. In the Time History Function Definition - Sine Box, on the right-hand side in the “Define Function” section, there are two

boxes that display the values of each step the function outputs during each cycle that was specified. As can be seen in **Figure 5.1.6**, the first value in the “Time” column is 0.01 seconds, which specifies the time step size of the input function. This must also be the time step size of the load case output, otherwise the sine function and load case will both run at different time steps. As a result, the curves may be more rectilinear than curved for some frequencies.

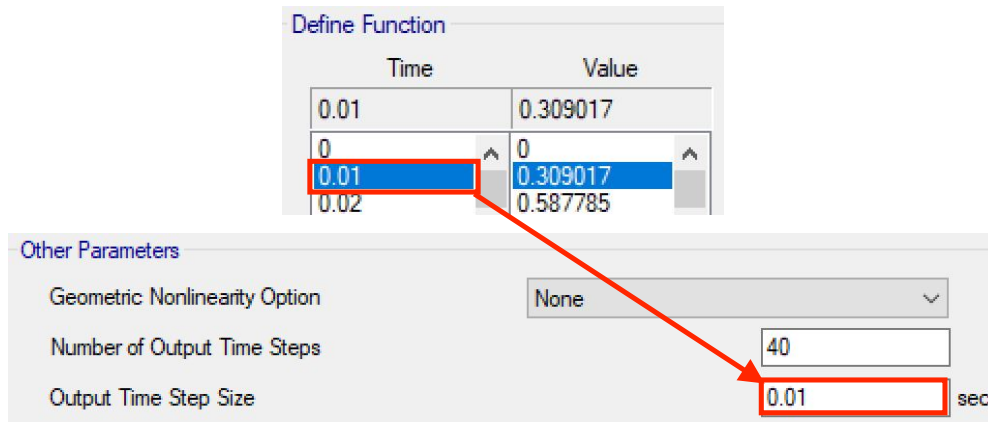


Figure 5.1.6 The value for “Output Time Step Size” must match the first value in the Time column of the “Define Function” section for each frequency ran.

Also important is that the value for “Number of Output Time Steps” in the Load Case Data Box matches the number of time steps the function will run, or else some of the data may not show up in the hysteretic curve. The correct input of time steps for the Load Case Data Box is found by looking at the “Parameters” section in the Time History Function Definition - Sine Box. Multiplying the “Number of Steps per Cycle” value by the “Number of Cycles” value yields the total number of steps that will be run, which is the input value of the “Number of Output Time Steps”, as seen in **Figure 5.1.7**.

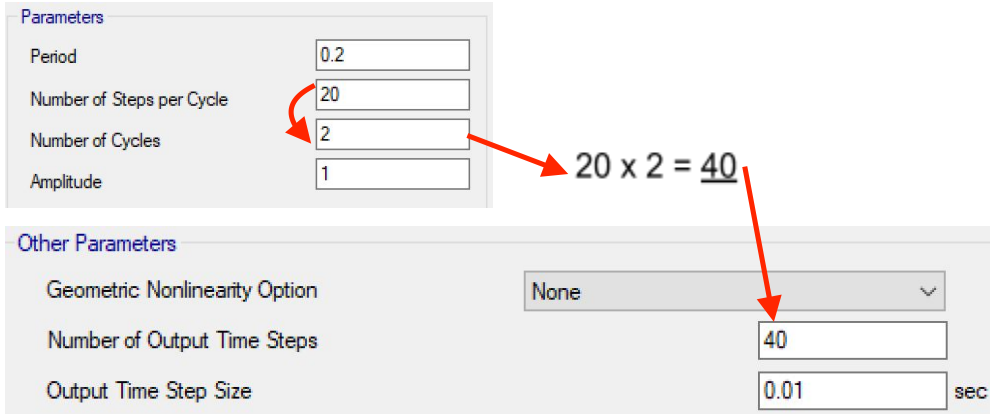


Figure 5.1.7 The total number of output time steps is found by multiplying the number of steps per cycle by the number of cycles, in this case: $20 \times 2 = 40$.

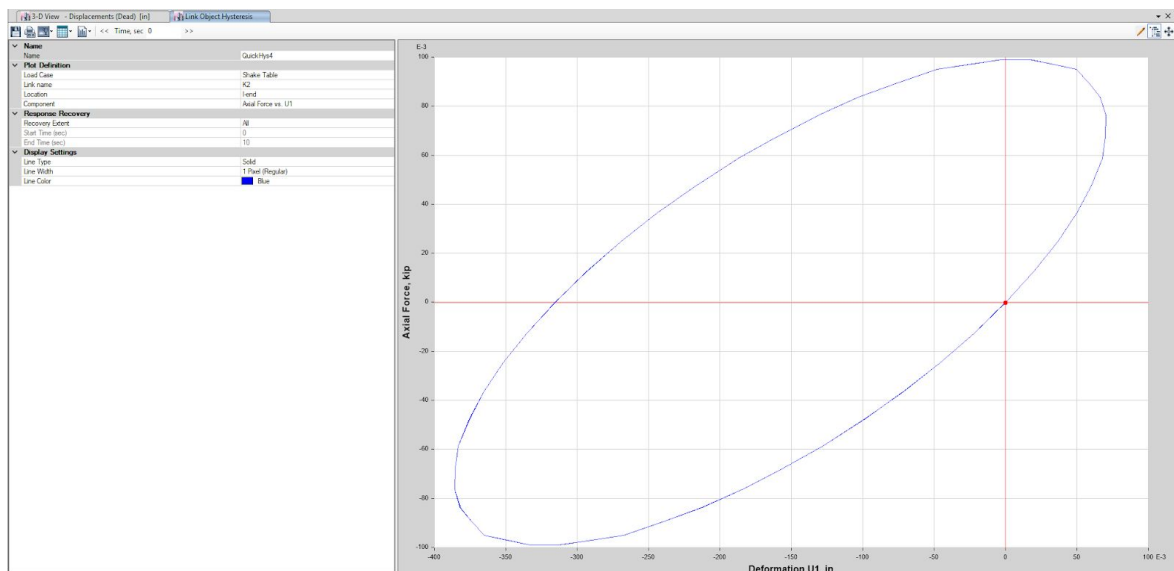


Figure 5.1.8 ETABS Hysteresis Curve [Display -> Quick Hysteresis -> Links]

In the Load Case Data dialog box, select a “Time History” Load Case Type, with “Nonlinear Direct Integration” as the subtype. Make sure the Initial Conditions box is set to “Zero Initial Conditions”, then input the loads to be applied using the Load Pattern and Function that were previously created. Run with the inputted values. Display the Quick Hysteresis of the Links, as seen in **Figure 5.1.8**.

Upon plotting the Hysteresis curve, the values are exported into excel for comparison with the Shake Table results. See Final Data Results *Section 6.1* for comparison.

5.2. Analysis

Once the ETABS model was created, it was now time to figure out the damping coefficient by means of trial and error. With time history functions created for each sine wave of interest, and certain input properties of the damper model held constant, a few variables could be iteratively changed to develop curves that matched the experimentally derived ones for the same frequencies. First, the Nonlinear Stiffness had to be set to a value that generated the proper hysteretic curve shape, which ended up being 10,000 lb/in. Then, individually between runs, the scale factor of the load, period of the sine wave, and damping coefficient were changed in small increments until curves were generated that made sense. Next, the periods were set to match the sine waves that were run through the shake table, so that the only variables left to change were the scale factor of the load and damping coefficient. For each frequency, the maximum load measured in the damper was noted from the data gathered on the shake table, and the scale factor adjusted to match that force, which then left only the damping coefficient to be iteratively changed through trial and error until the ETABS hysteretic curve matched almost exactly the shake table curve.

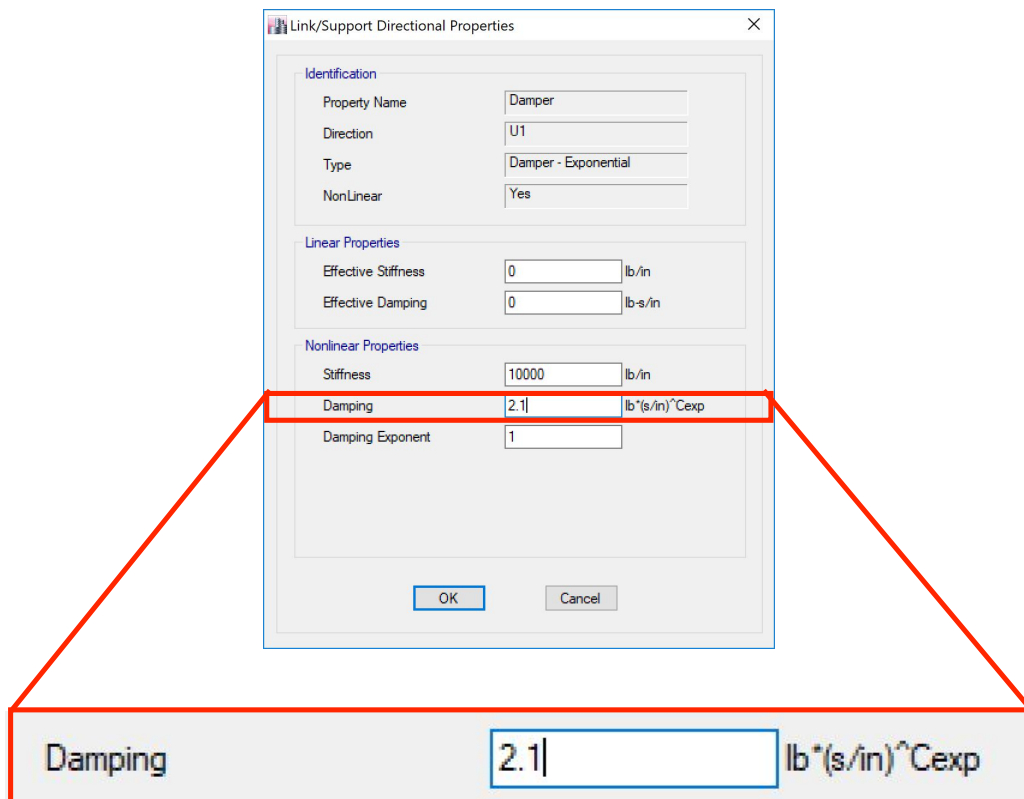


Figure 5.2.1 Damping Coefficient in ETABS

6. Data

After running the multiple tests for frequencies ranging from 1 Hz to 10 Hz, along with displacements ranging from 1,000 mVpp to 4,000 mVpp, the students exported the data from LabView to Excel. Then, they created hysteretic curves for multiple frequencies ranging from 2.5 Hz to 10 Hz, and at the various displacements, as discussed in “Testing”.

6.1. ETABS/Shake Table Comparison

The testing and results were analyzed and used to find the damping coefficient of this specific viscous damper that was given to us for this project experimentation. For this analysis, only frequencies of 2.5 hZ to 10 Hz were used, and all of them at a displacement voltage setting of 1,000 mVpp. Though the data was gathered and curves generated for both the unfiltered and filtered data, only the filtered curves were compared to the ETABS curves. This was decided by the authors and their advisors to be the best course of action considering that the unfiltered data could have possibly picked up ambient vibrations and other electrical noise that skewed the data and made the curves irregular.

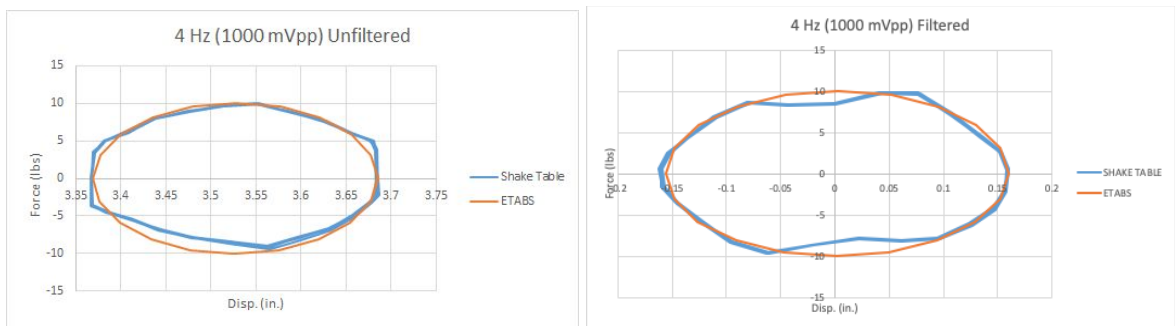


Figure 6.1.1 Shake Table and ETABS Hysteresis Curves for 4Hz (Unfiltered and Filtered)

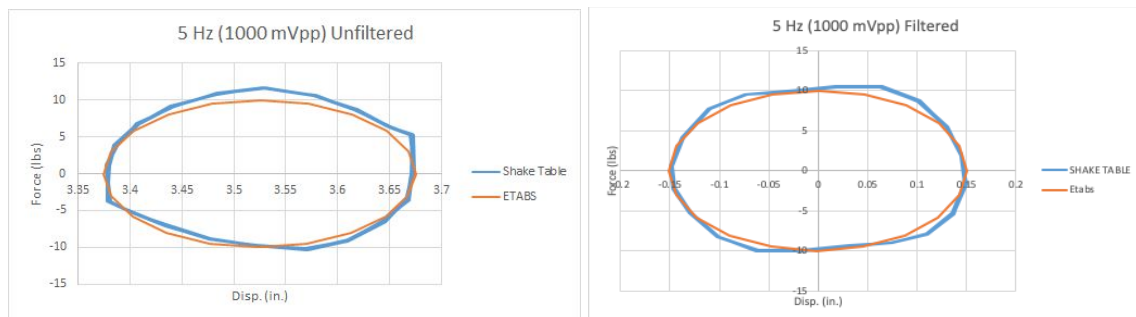


Figure 6.1.2 Shake Table and ETABS Hysteresis Curves for 5Hz (Unfiltered and Filtered)

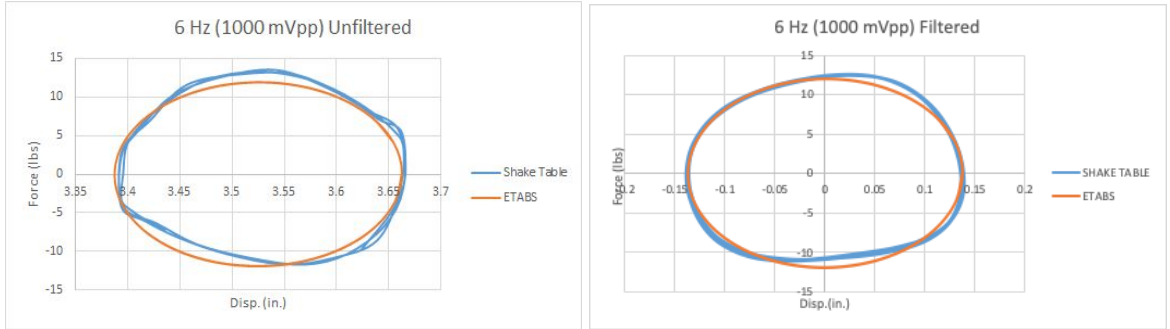


Figure 6.1.3 Shake Table and ETABS Hysteresis Curves for 6Hz (Unfiltered and Filtered)

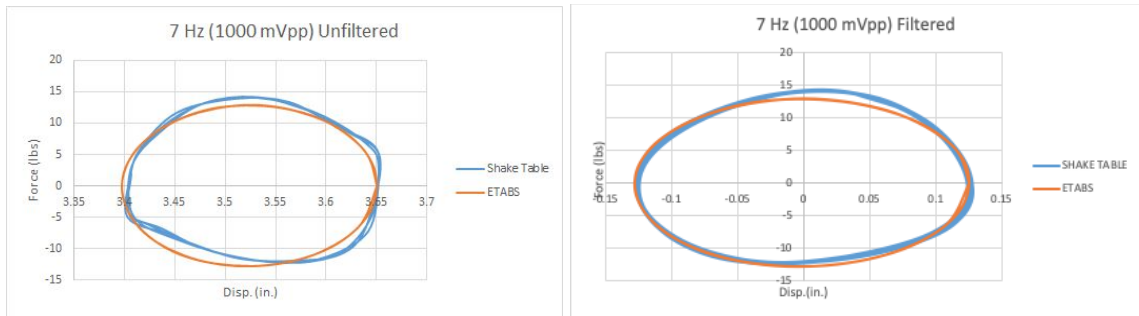


Figure 6.1.4 Shake Table and ETABS Hysteresis Curves for 7Hz (Unfiltered and Filtered)

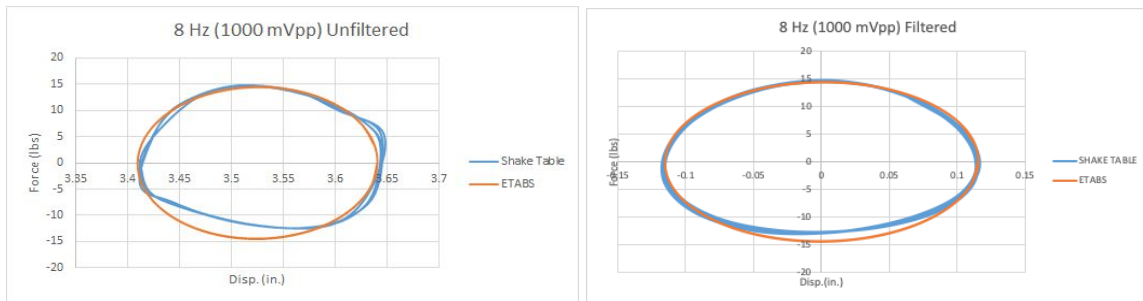


Figure 6.1.5 Shake Table and ETABS Hysteresis Curves for 8Hz (Unfiltered and Filtered)

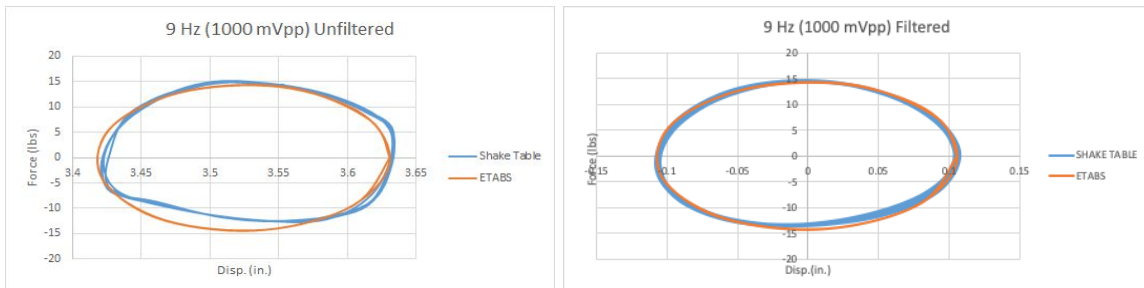


Figure 6.1.6 Shake Table and ETABS Hysteresis Curves for 9Hz (Unfiltered and Filtered)

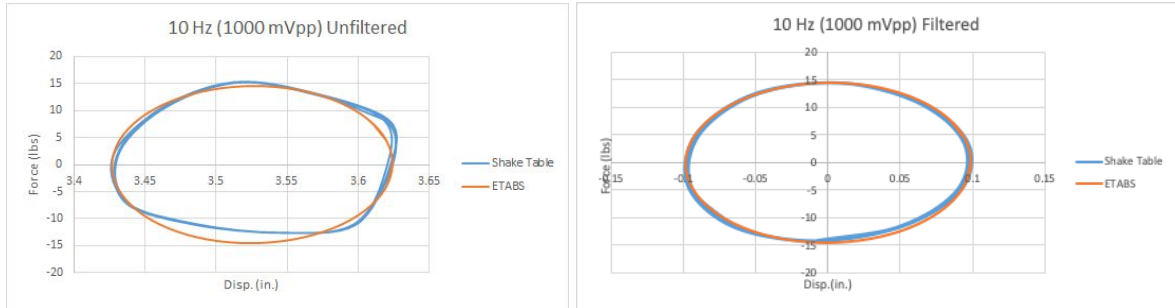


Figure 6.1.7 Shake Table and ETABS Hysteresis Curves for 10Hz (Unfiltered and Filtered)

$$F = CV^{\alpha}$$

Frequency	Damping Coefficient (C)	Scale Factor	Damping Exponent (α)
4 Hz	2.50	10	1
5 Hz	2.10	10	1
6 Hz	2.30	12	1
7 Hz	2.32	13	1
8 Hz	2.38	14.5	1
9 Hz	2.48	14.5	1
10 Hz	2.31	14.5	1

Table 6.1.1 ETABS / Shake Table Inputs

From the values above, the authors calculated an average value of 2.34 lb-s/in for the range of 7 frequencies. This value may now be applied to this particular damper when it is being used from seismic analysis and design projects or experiments. Worth noting is that the damping exponent (α), was held constant at a value of one for all seven ETABS analysis runs. This was because a value of one makes the hysteretic a near perfect ellipse, while any lesser value warps the curve into a more rounded-rectangular orientation. Since the shake table hysteretic curves generally followed an elliptical shape, the ETABS curves fit best over the shake table curves when a damping exponent of 1 was used.

7. Conclusion

7.1. Considerations

This project and experimentation considered global, economic, environmental, and social effects. In recent years, there has been an increase in demand for dampers and base isolation systems for building technology as building resilience becomes popular. Dampers improve building performance for building occupancy after an earthquake by dissipating energy, reducing the seismic demand and damage to buildings. Japan and the United States are both technologically advanced countries concerned with protecting the public from earthquakes. Japan, where earthquakes are more common than the US, has built more resilient structures capable of withstanding earthquakes and able to be occupied immediately afterwards via government mandates and engineering codes for base isolation systems [3]. By contrast, the United States has a minimum and less protective standard with the understanding the buildings will be damaged after the earthquake [3]. Base isolated systems have been installed in the United States, though not as commonly as Japan. Seismic engineering in the United States has been commonly based on the notion that a building will be torn down and rebuilt within fifty years, meaning there is less of a chance that some buildings experience a significant earthquake [3]. When an earthquake hits, most US buildings are designed to absorb energy through the intentional yielding of structural members in specific locations (typically in beams and girders), making the structure more ductile during excitation. Thus, many United States buildings are likely to suffer significant (yet expected) damage during a design level earthquake, and may not be fit for immediate occupancy, let alone its function after the shaking has subsided.

With damper implementation, buildings can function after an earthquake and reduce reoccupancy cost. Base isolation systems combined with or separate from damping devices can be a part of damage-resistant building design. Base isolation systems are costly as the entire structure must be supported on elastomeric or sliding bearings but dampers provide a less costly alternative while still significantly improving the performance. A multi-year federal study concluded that fixing buildings after an earthquake costs four times more than designing the buildings more resilient in the first place [3]. If buildings are built for resilience, there will be fewer buildings being completely rebuilt, decreasing the carbon footprint of construction and lessening the environmental and economic impact on society. This cannot happen without designing and updating building codes. By delaying more strict building codes, the United States loses \$4 billion per year [3].

For dampers to be designed more effectively, digital modeling and nonlinear analysis of dampers in structures is necessary. By modelling through ETABS, this damper can be used for future references and senior projects under different parametric studies. Modeling dampers with ETABS is a delicate process, since there are many factors that affect the properties and response of the model. To ensure proper analysis of a damper, especially the damper used in this project, it is recommended that the damper be modeled as a link and characterized as nonlinear. The linear properties of the damper are set to zero, since the behavior of a viscous damper is velocity-dependent. The orientation and direction of the model damper are also important, since the forces and motions ran through it must be in its principal direction of expansion/contraction. Through experimentation with this viscous damper, the results given have shown how a damper can absorb energy at different frequencies.

In addition to conducting frequency dependent test, preliminary testing with the dampers under El Centro, Northridge, and Kobe ground motions were conducted. When using the dampers in the 3 story REEFA structure, Reeve and his group noticed that the dampers decreased the deflections of each floor by about 5% [9]. Now that the damper properties have been characterized, the dampers can be used for future undergraduate and graduate projects. For the REEFA structure, this can include and not be limited to future experimentations on the effectiveness of the REEFA damper arrangement, a base isolation design system comparison, and damage simulation testing with and without the dampers [9]. Considering that the REEFA structure experienced resonance at high frequencies (upwards of 10 to 15 Hz), and that the damper performed best at higher frequencies, the dampers used in this project are a good fit.

7.2. Lessons Learned

At the conclusion of this project, the authors learned how to operate a shake table and acquire the resulting force, acceleration, and displacement data using LabView Signalexpress. In addition, the authors gained a deeper understanding on utilizing ETABS to model a viscous damper and a hysteresis curve. The authors learned that link objects in ETABS can be used to accurately model the nonlinear force-velocity relationships of viscous dampers with damping properties based on the Maxwell model of viscoelasticity [7]. Under different parameters, the authors observed how the damping coefficient, scale factor, damping exponent, and frequency can impact the force-displacement hysteresis curve.

The authors also learned how important viscous dampers can be when installed in buildings for earthquake building resilience. They researched the differences between dampers, such

as a friction versus viscous damper. The authors were able to observe and predict the effects of different frequencies on the behavior of the viscous damper via hysteretic curves. Lastly, the authors are more likely to consider the use of viscous dampers to improve building resilience in future projects.

8. Further Research

Further Research Objectives:

- Compare actual behavior of the damper under seismic loading with predicted behavior through analysis calculations.

This project focused on the properties of a viscous damper when subjected to oscillatory motion of specified frequency and displacement. However, if this project were to be expanded for future research, it would be an interesting concept to consider what effect the damping coefficient of a damper would have on its performance during an earthquake. In the same fashion as was done for the sine waves, notable earthquake time histories can be run through the damper on both the shake table and in the ETABS model, and then the damping coefficient (perhaps along with other properties) can be iteratively changed until the hysteretic curves match. In **Figures 8.1.1-8.1.3**, these kinds of hysteretic curves, which were already generated during this project for trial, are displayed.

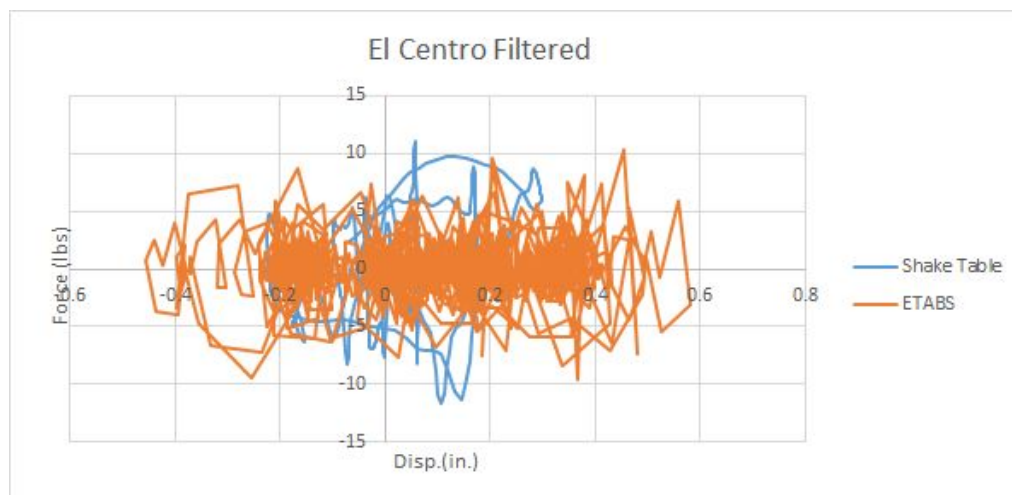


Figure 8.1.1 The Overlapped Hysteretic Curves of the El Centro Earthquake

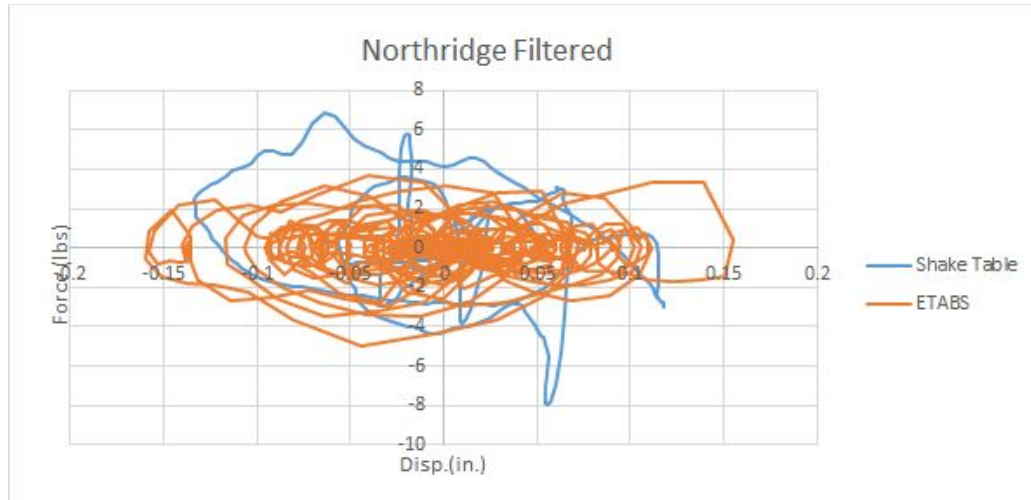


Figure 8.1.2 The Overlapped Hysteretic Curves of the Northridge Earthquake

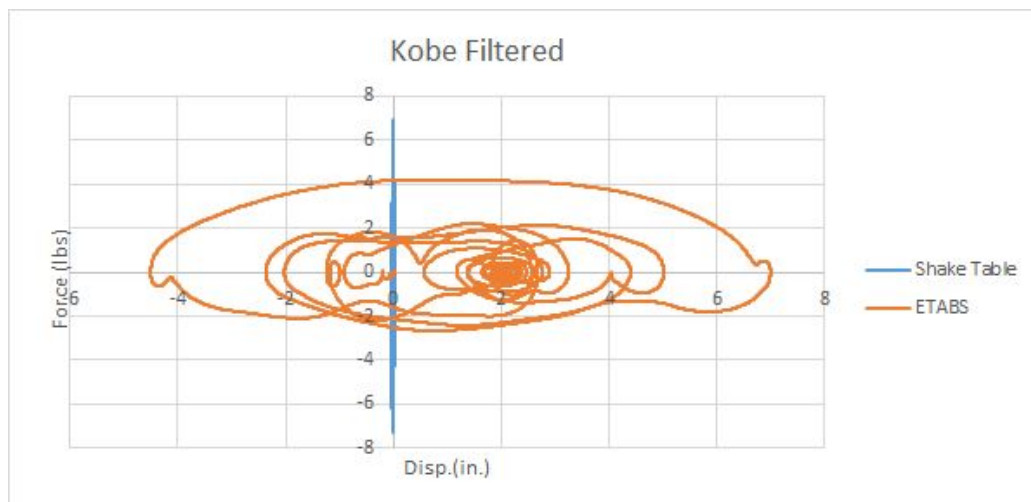


Figure 8.1.3 The Overlapped Hysteretic Curves of the Kobe Earthquake

As can be seen by the hysteretic curves, the shake table and ETABS model do not exhibit the same behavior for each of three earthquakes, most notably with the Kobe earthquake. There are many factors that can contribute to the severity of these differences in shape and values. Some of these include the accuracy of the tools used to measure force, displacement, and acceleration in the shake table, the units used in the input time histories for each earthquake (which affects the value of the scale factor in ETABS), etc. For future research of this kind with the same damper, these factors would be further explored and understood.

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