Implementation of Fluid Viscous Damper for 2023 EERI Seismic Design Competition

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Senior Project

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Abstract

The authors of this report were a part of the 2023 Earthquake Engineering Research Institute (EERI) student chapter for California Polytechnic State University, San Luis Obispo (Cal Poly). With thirteen other team members, they traveled to San Francisco, CA to compete in the Seismic Design Competition (SDC) hosted by EERI. The team was tasked with preparing a written proposal, design and computer analysis of the structural system, construction of two physical models, as well as creation of a poster and a presentation for a proposed mid-rise building located in the competition host city. The goal of the design of Cal Poly building "Lucid Towers" was to achieve seismic resiliency while integrating characteristic elements of San Francisco architecture.

The senior project group was specifically responsible for the design, implementation, and analysis of supplementary dampers in the structural system. These efforts were to improve the structure's performance during the two competition earthquake ground motions and therefore reduce the seismic cost of the building. This report serves as an important team record, since there is no existing Cal Poly team documentation from past years on the process of selecting, testing, and implementing a damping system. Therefore, the report outlines both the overall process of implementing dampers into the structural system for the 2023 EERI SDC competition, as well as details on physical testing methods and calculation approaches used to quantify the dynamic response of the dampers.

Acknowledgements

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Lastly, a special thanks to the team faculty advisor Anahid Behrouzi. The team could not have achieved its goals without her guidance and positive reinforcement.

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1.0 Introduction to EERI Seismic Design Competition

Every year the Earthquake Engineering Research Institute (EERI) hosts an international undergraduate seismic design competition (SDC) to encourage students to research earthquake engineering principles through the design, construction, testing, and analysis of a mid-rise (5-ft tall scaled balsawood) building to resist two simulated ground motions. For the 2023 EERI SDC teams were tasked with designing a structure for San Francisco consisting of two narrow towers connected via a series of sky bridges where the lower bridges were a single story height and the upper was a double story height.

The team's goal was to address the competition problem statement in a way that would blend the traditional and modern elements of the San Francisco skyline to achieve both a resilient and environmentally sustainable structure. In keeping with the themes of sustainability, transparency, and progress, the structure was named "Lucid Tower". By utilizing steel and glass materials in the façade design, Lucid Tower mimics local monuments such as Uber Headquarters that incorporate sky bridges (as shown in Figure 1) and the use of curved symmetric elements as an homage to the iconic suspension cables of the Golden Gate Bridge. To accomplish the resiliency and sustainability goals outlined by the competition, the team decided to implement a supplementary damping system into the structure.

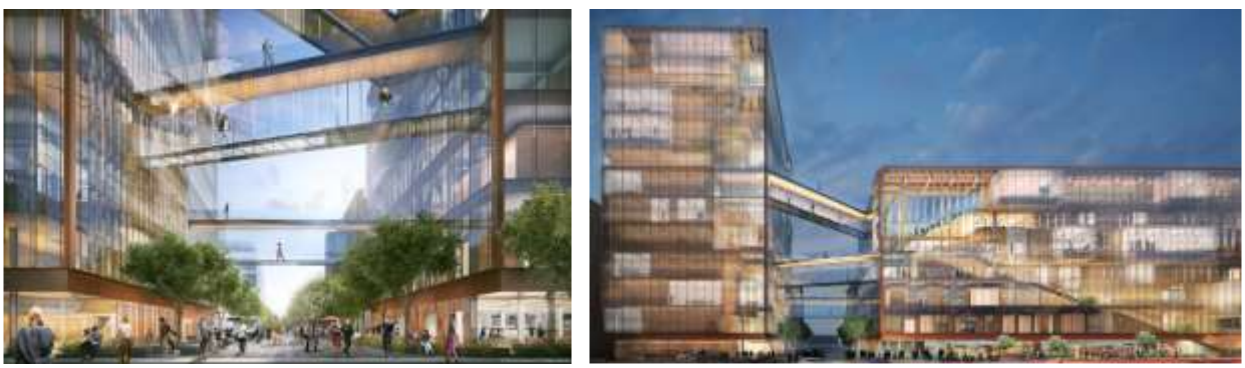

Figure 1: Design Precedent - Uber Headquarters in San Francisco, CA
(Image Credit: SHoP Architects)

1.1 Scope of Competition Submission

The SDC organizing committee publishes an official rules document, a design guide, and a damper design guide in mid-late October for the competition the following April. Once students form a team to represent their respective university, they must submit a written design proposal by mid-December to secure a spot in the competition. As indicated in Section 1.1 of Robinson [1] the proposal covers multiple basic topics related to seismic design and encourages students to explore the importance of architecture, structural design, economy, environment, and stakeholder needs. This proposal's score contributes to the team's performance in the communications category, yet there are numerous technical engineering and construction considerations involved in overall scoring, including bonus points for successfully implementing a supplementary damping system into the structure.

If a team wished to include a damping system in their structure, they were required to submit an additional damping proposal document by early January that described the system and to receive approval to proceed with implementing the specified damper type. The incentive of bonus points and a general curiosity on the topic of supplementary damping drove the authors' further exploration of researching, testing, and analyzing different damper systems. The 2023 EERI Seismic Design Competition damping device approval process and proposal requirements as well as the proposal submitted by the Cal Poly team are included in Appendix A.

As a note to readers, the damping system the team decides to implement in any given year must be different than any system their school's teams may have presented in the five preceding years of the competition. Although the damping system described in this report cannot be used in consecutive years, the testing methods to describe the dynamic properties of the system would be similar. Another word of caution, if the SDC committee decides that the approved damping system described in a team's proposal is different from that in the physical structure brought to competition, this can lead to a disqualification. With that in mind, the damping system must be separate from the structural system, ensuring that it can be removed without compromising the model's structural integrity.

1.2 Background on Supplementary Damping

Imagine throwing a baseball and it traveled 100 feet before coming to a complete stop. Now imagine throwing that baseball, the exact same way as before, but underwater. Would the baseball travel 100 feet before coming to a complete stop? No, reason and experience would indicate that baseball would not travel 100 feet, in fact it might not even travel 10 feet! In this example the water is acting as a damper to the baseball's motion. The water dissipates the baseball's kinetic energy into heat as the baseball moves resulting in the ball traveling slower and stopping sooner than before. Other examples of dampers include shock absorbers in a car, a bike, and even a door.

There is an emphasis in the structural engineering industry to design more resilient structures that can resist seismic forces with limited damage. Some new techniques include introducing dampers into the structural system to reduce stresses and forces in the building. This enables a reduction in the amount and size of structural members needed as well as repair costs since many of the key structural members will stay intact due to the dampers' significant contribution to energy dissipation during a severe seismic event. Dampers have been shown to be one of the most effective seismic force resisting systems. Through many years of research and experiments, they have proven to increase a building's damping from about 5% to 15% [2]. Additionally, damping systems can also be used to increase, decrease, or maintain a building's stiffness to achieve a period with a more desirable response give a site's design spectra. Details on different damping approaches for structural engineering applications are in Chapter 2.

1.3 Purpose of Implementing Supplementary Damping

The use of dampers in the Cal Poly team submission to the 2023 EERI SDC competition was to introduce a more effective seismic force resisting system that would reduce member sizes to result in a more sustainable and lightweight building. Although past years' teams had conducted preliminary investigations of implementing damping systems, these efforts had never been realized in their competition structures. Damping systems can be complicated to effectively characterize and then integrate into either the physical or ETABS models. Since damping approaches are not covered in depth in the typical undergraduate curriculum, this results in a significant learning curve and increased workload for a team that does take on this challenge.

This report aims to encourage and equip future EERI SDC teams to incorporate supplementary damping in their competition structures. Chapter 2 introduces various damping system options as well as elaborates on their holistic benefits to buildings; Chapter 3 outlines the testing equipment and methods to characterize the response of an individual viscoelastic damper; Chapter 4 summarizes the results and observations from shake table testing of the prototype building model with supplementary damping implemented; and Chapter 5 provides conclusions on the successes and lessons learned of the 2023 team through this process. Ultimately, this report hopes to give future students a firm foundation and clear direction on how to proceed with the implementation of damping systems.

2.0 Damping Approaches Considered & Final Selection

The first step taken in the process of implementing a supplementary damping system into the EERI SDC competition structure was an investigation of different methods of damping to understand how each system effects the response of the structure and which would be best given the constraints of the competition and the structural performance goals. There were four damping systems that were considered and researched: fluid viscous damper, fluid viscoelastic damper, friction damper, and a rocking shear wall. The reader may note that approaches like a mass damper – either in the form of a swinging pendulum or sloshing tank – which are options used in real-world structural applications were not considered due the significant added mass and the challenges of modelling their nonlinear damping behavior.

2.1 Damping Approaches Considered

2.1.1 Fluid Viscous Damper

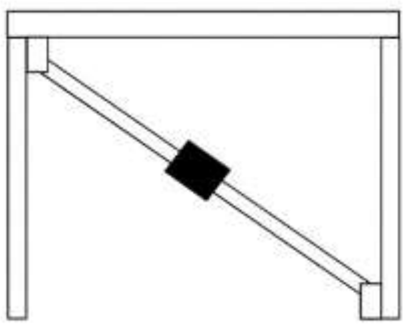

Figure 2. Fluid Viscous Damper

The basic principle behind fluid viscous dampers involves the use of hydraulic fluid (synthetic oil) that when the structure experiences dynamic movement, the fluid within the damper is forced to flow through specially designed valves or orifices in a perforated piston head. This flow of fluid generates a restorative damping force that opposes the motion of the structure, effectively absorbing and dissipating the energy in the overall system, thus reducing the amplitude of the vibrations and forces that structural members experience. As shown in Figure 2, the damping device is typically aligned with an extender brace within a frame configuration [2].

The effectiveness of this type of system is dependent on relative movement between the nodes of the extender braces, which means the structural system needs to experience relatively significant deflections for this damper to dissipate energy. A benefit to this system is that it can be designed in a manner that adds no additional stiffness to the system, since shortening the building period often leads to increased acceleration and therefore force demands.

To learn more about this type of device, the team met with Nathan Canney, PhD, PE who is the Director of Structural Engineering at Taylor Devices, Inc. This company designs, fabricates, tests, and provides damping solutions to many industries including structural engineering applications. Specifically, he was able to provide technical insights about the benefits and drawbacks of the fluid viscous damper and some considerations for implementing it in the competition structure. He also provided two useful documents he co-authored on design and computer modeling: “Pre-Northridge Steel Moment Frame Retrofit Design Guide” [3] and “Viscous Damper Modeling Design Guide” [4]. It is recommended that future teams seeking to employ similar dampers reach out to Taylor Devices for guidance and review these publications.

Besides these meetings, review of two past senior projects that involved viscous damping was also conducted [5 and 6], a summary of these findings are presented in Appendix B.1.

2.1.2 Fluid Viscoelastic Damper

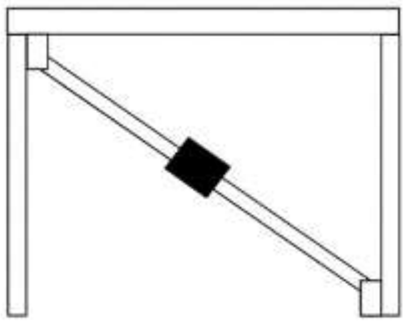

Figure 3. Fluid Viscoelastic Damper

Like with the fluid viscous damper, this system contains viscous fluid to dampen the system. However, these dampers also integrate viscoelastic material, such as rubber or a spring, such that the final product exhibits both viscous and elastic behavior. This combination of material properties and fluid flow allows the damper to absorb and convert the kinetic energy from the dynamic loading of the structure into heat, thereby reducing the amplitude of vibrations and loading the structure experiences. As shown in Figure 3, the damper would also need to be aligned with an extender brace within a frame.

Another similarity to the fluid viscous damper is that this system is dependent on relative movement between the nodes of the extender brace, but a major distinction is that it will add loading to the building as its elastic qualities will try to return the damper and the connecting structure back to its original state after deformations. This adds stiffness to the structure which will change its overall behavior under dynamic loading.

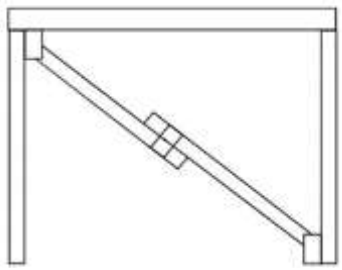

Figure 4. Friction Damper

2.1.3 Friction Damper

These dampers dissipate energy by using friction between two surfaces to convert kinetic energy into thermal energy. The benefit of using a system like this is its simplicity and efficacy. These dampers are easy to construct, maintain, and have a comparable damping effect to the other systems. Additionally, similar to the previous system, friction dampers add stiffness to the system due to the resistance of static friction.

To gain more knowledge on this type of device, the team met with Matthew Kyler, PE who serves as the Principal at Kyler Engineering. Lessons learned from this discussion was that the most used type of friction dampers is in the form of friction pendulum bearing damper where a disk or puck slides between convex and concave surfaces dissipating energy in this manner, common as base isolation. However, isolation approaches are specifically not permitted for the EERI SDC competition. Therefore, another alternative was discussed that involves steel-on-steel friction (with or without rubber pads) like those developed by Tectonus [7] that can be aligned with an extender brace or wall member. These devices do need to be placed at locations where relatively large displacements and forces are expected to be able to overcome static friction and activate the damping response.

Further brainstorming around this concept for application to the competition structure led to a possible design of a friction damper at the midspan of the brace, like that shown in Figure 4, where there were teeth in opposing directions with a material in the middle of teeth to generate the necessary friction to damp structural response. There have also been past competition teams that utilize brace members with sandpaper and elastic bands to achieve a similar goal.

2.1.4 Rocking Shear Wall

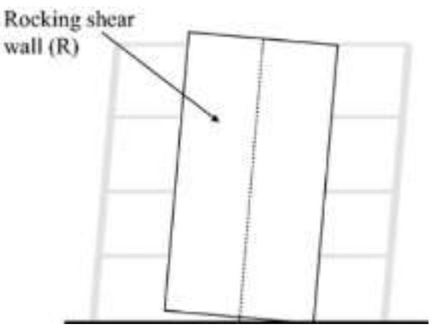

Figure 5. Rocking Shear Wall

As shown in Figure 5, timber rocking shear walls involve the use of partially unbonded tendons (post-tensioning cables) along the height of the wall panels and secured into the foundation, and at the wall-foundation interface there can be additional energy dissipation in the form of fluid viscous dampers or a buckling-restrained braces. Use of a rocking shear walls within buildings has been shown to accomplish two goals: it adds damping and acts as a lateral force resisting system. The basic design strategy aims to dissipate seismic energy and reduce lateral forces by promoting controlled rocking motion of the building and where damage will occur. The rocking action redistributes forces from shear throughout the wall to tension forces at the base. There is additional damping when damage occurs at the corners of the base of the wall and in the flexural mechanisms within the wall during rocking. Based on a study by Aragaw and Calvi on rocking shear walls, damage is reduced in a rocking shear wall system but the overall structure experiences somewhat higher [8]. Overall, this system dissipates seismic energy while maintaining building stability and resisting dynamic loading.

To gain a greater understanding of this approach, the team reached out to Sydney Gallion, PE who is an Engineer with Forell | Elsesser, Inc. a firm that is known for providing innovative solutions to seismic design challenges including base isolation, passive damping systems, and cross-laminated timber (CLT) construction. Specifically, Sydney's graduate research involved interlocking rocking CLT shear walls linked by viscous dampers [9] and a major project at her firm had just been completed at the University of California – San Francisco campus utilizing a similar approach [10]. A summary of the major lessons learned from this conversation and review of the two previously mentioned documents are summarized in Appendix B.2.

2.2 Selected Damping System

The fluid viscous damper was chosen as the system to implement into the EERI competition structure due to the versatility and efficacy in absorbing and dissipating dynamic energy that could adequately achieve the desired results of reduced accelerations and displacements of the braced-frame structure. Beyond that, it was the only system that did not add stiffness to what was already determined to be a very stiff structure. With encouragement from industry professionals, a commercial damper product would be chosen as opposed to a custom designed and fabricated damper by the team. This would make the process significantly simpler from the perspective of construction of the physical model, quantifying the damper's dynamic properties, and incorporating it into the ETABS model.

After researching various options, the Bansbach Easylift FPD-1030B3-CW was chosen due to its affordable cost, efficient design, small size, and light weight to meet the various competition parameters. This damper was sourced through Amazon from the Bansbach Easylift storefront at a cost of $9.25 per damper. The team purchased twenty-five dampers and it took approximately three weeks to deliver.

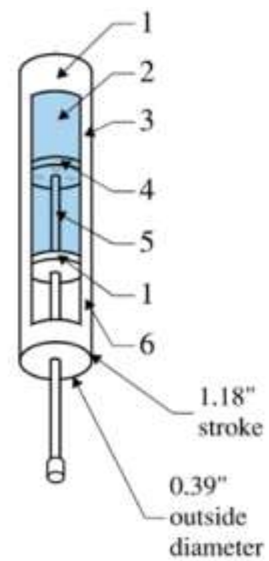

Figure 6. Bansbach Fluid Viscous Damper

Per the specifications sheet provided by the manufacturer, the damper dimensions are 4.18 x 0.39 x 0.31 inches with a 1.18-inch stroke [11]. This damper is constructed of an oil filled cylinder housing a perforated piston, which facilitates the transfer of fluid within the oil filled chamber. In response to lateral forces acting upon the structure, the piston undergoes compression or extension to mitigate vibrations. This damping mechanism is depicted in Figure 6, with labels denoting the various components:

(1) End covers of the fluid chamber,
(2) Damping medium,
(3) Cylinder block,
(4) Perforated piston,
(5) Piston rod, and
(6) Cylinder chamber.

3.0 Structural Design & Damper Integration

3.1 Structural Design of the Competition Model

To address the competition problem statement, the mid-rise balsawood structure consisted of two identical towers – one residential and one commercial – connected at various levels by skybridges. The area for each tower was 5.5-in and 14-in with a 3-in space in between. Skybridges were 3-in by 3-in square in plan and 3-in tall, except for the top skybridge which was a double-story height of 6-in. The final design for the Cal Poly team is shown in Figure 7 where the architectural program is color-coded on the North/South face elevation and Floor 12 plan views (yellow = residential, red = retail, blue = commercial).

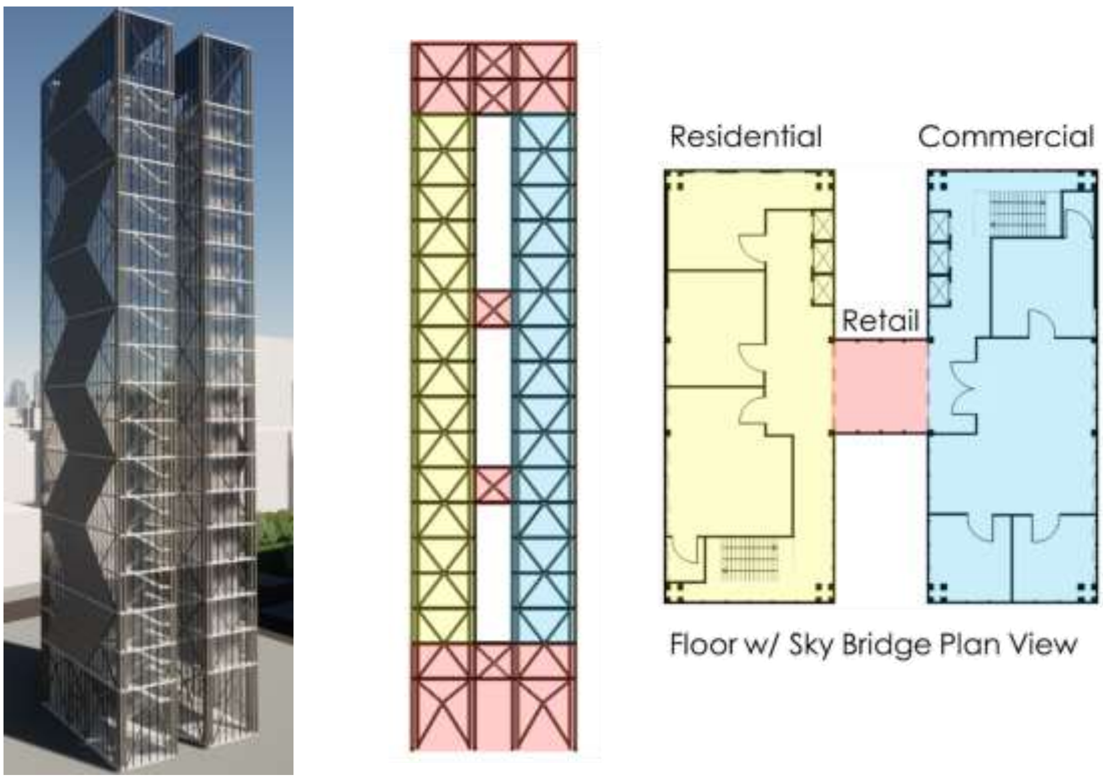

Figure 7. Architectural Design: (a) Render, (b) N/S Elevation, and (c) Floor 12 Plan View

In the elevation view, the structural system consists of four columns bundled together at the exterior corners and braces around the perimeter of each narrow tower to provide a continuous path for both gravity and lateral load. The larger 6-in by 6-in bays have concentric braces that span two stories, while the 3-in by 6-in bay on the East and West faces has concentric braces that only span one story. There is also only a single layer of braces on the East and West faces, with a double layer for additional stiffness in the short direct of the narrow towers on the North and South faces. The exception to the concentric brace pattern is in the first story that was required to have a double-height clearance to accommodate the building lobby and these braces are similar to an optimized frame where the intersection point of the members is located above the story mid-height.

In terms of the floor diaphragms, there were five unique designs shown in Figure 8 to accommodate whether a floor was subjected to dead load (threaded rod with weights at floors 4, 7, 10, 13,16), the location of a skybridge, and/or the presence of the damper extender brace.

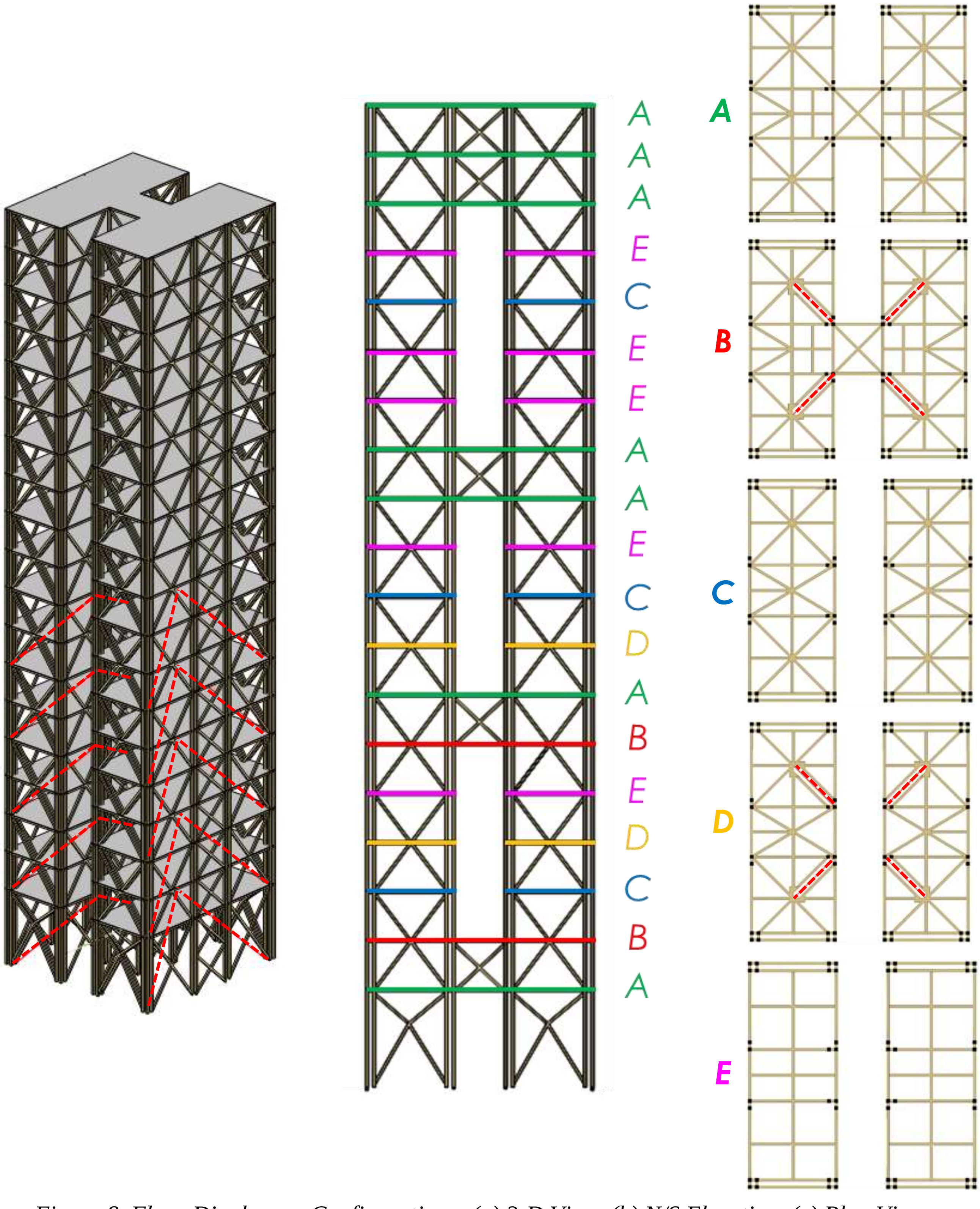

Figure 8. Floor Diaphragm Configurations: (a) 3-D View, (b) N/S Elevation, (c) Plan Views

To elaborate on the Figure 8, configurations are used when:

(A) Skybridge with or without floor dead load
(B) Skybridge with penetration from damper extender brace
(C) Floor dead load
(D) Penetration from damper extender brace
(E) Unloaded floor

Related to diaphragm configurations A and B, bracing creates a continuous "x" through the skybridge to the corners of the individual towers to avoid horizontal load path discontinuity. For diaphragm configurations B and D, the dampers are located in pairs for the bottom nine stories of each of the towers and each span 6-in (typically two-story heights), which can be seen as red lines on Figure 8(a) and 14. The dampers require a penetration every other floor where their extender braces intersect the floor plan. The dampers are configured in this manner – rather than being aligned with the exterior braces shown in Figure 14 – to maximize their relative displacement between to activate the damper during the ground motions, and so access point requirements to count the full rentable floor area would be met. These design decisions are described in greater detail in Section 3.2.3. Lastly, the distinctions between diaphragm configurations C and E result from the lateral load flow that needs to be resisted on floors with threaded rod and weight masses attached compared to material efficiencies that can be taken for floors without these loads.

3.2 Integration of the Damper into the Structural Model

3.2.1 Design of the Damper Connection Caps

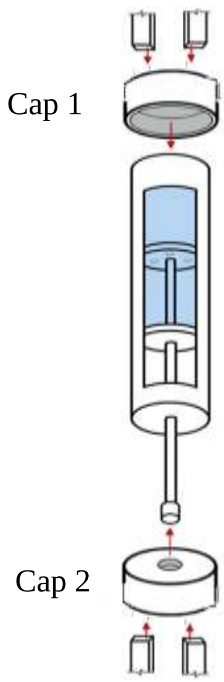

Figure 9. Damper Cap Connection

In order to integrate the dampers into the balsawood structural model, each damper needed to connect an extender brace and then to bundled columns at every other floor level. Therefore, it was necessary to design a damper connection that met two goals: (1) robust performance during the shake table ground motions and (2) optimization of material efficiency to achieve a lightweight structure. For the custom fit needed for Cap 1 and 2 between the damper and two balsawood members of the extender brace, 3D printing was selected as the fabrication approach. The team had access to Original Prusa i3 MK3 3-D printers in the Cal Poly College of Architecture & Environmental Design Digital Fabrication Laboratory (CAED dFab Lab). The most efficient and lightweight material suitable to construct the caps that could be used with these printers was determined to be polylactic acid (PLA).

The first steps to create the 3D printed caps were to sketch out a few possible solutions for the damper connections. The first design consisted of two caps based on the configuration of the already chosen design of bundled columns and damper type. As shown in Figure 9, the damper had different radii on each end necessitating two different cap designs for a damper. Each cap included three extrusions: one for the damper and two for the balsawood extender braces.

A prototype of each design iteration for Caps 1 and 2 was fabricated using the 3D printer and assessed for changes to better achieve the connection performance and material efficiency goals. The first iteration in Figure 10(a) was cylindrical with three penetrations that provided a precise friction fit for wood members into the cap. The second and third iterations in Figure 10(b) reduced material by including an extrusion at the center of the side where wood members attach, the difference in these iterations was edge chamfering and size reduction of the cap.

The final iteration shown in Figure 10(c) focused on the reuse of the caps from the prototype building model for the competition model. To create a connection that would withstand lateral forces from the earthquake ground motions, it was essential to glue the wood extender braces into the caps' friction slots. As a result, the forty caps were modified to have four penetrations, allowing each cap to be reused for both structural models instead of printing eighty caps. This led to significant material and time savings since printing the two end caps for each damper took up to 1.5 hours. Transfer of the damper system from the prototype to the competition model required that each damper connection be cut from the wood extender braces on the prototype model, the caps rotated 90-degrees and new wood braces be placed in for the competition model.

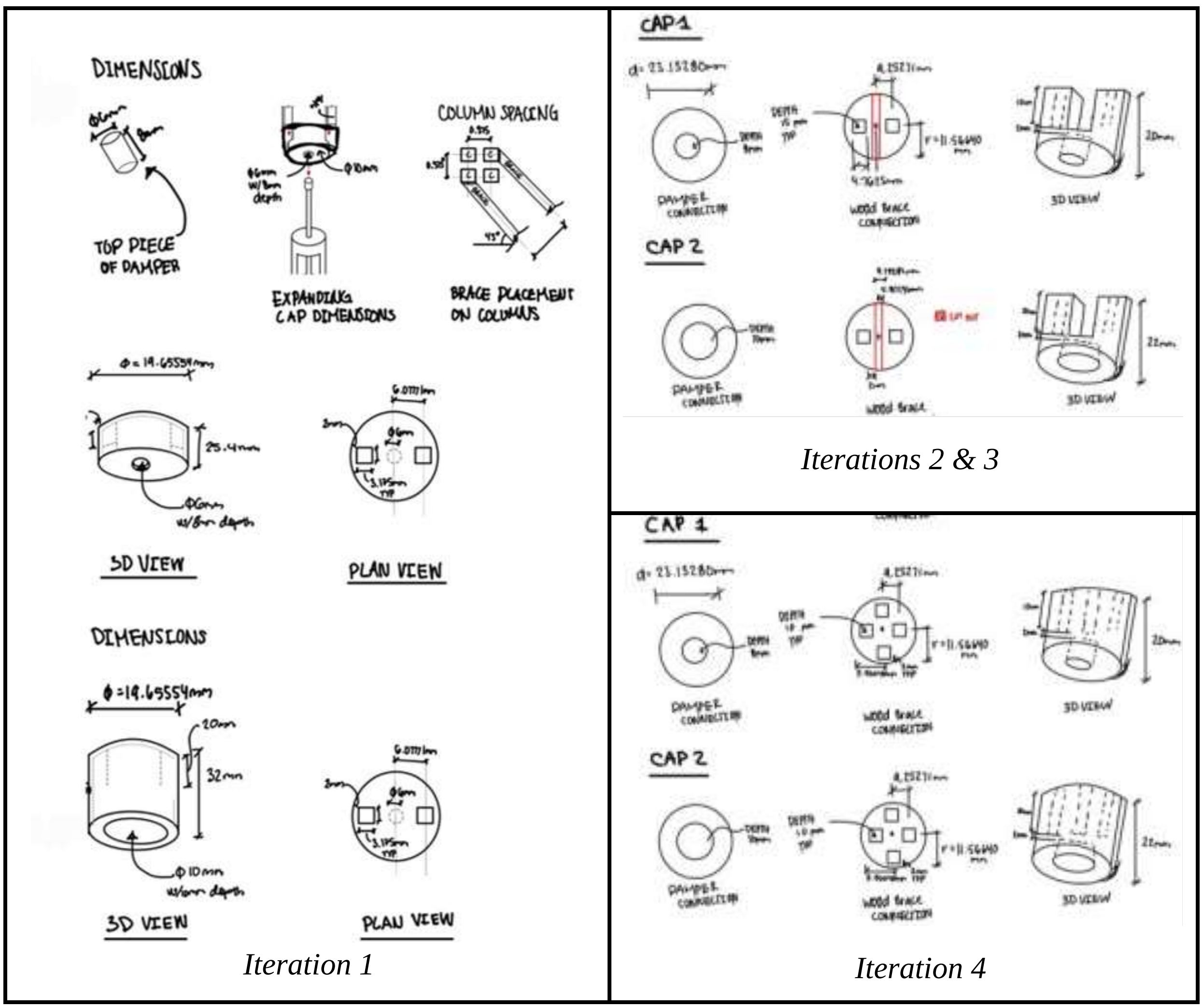

Figure 10. Cap Design Iterations: (a) Iteration 1, (b) Iteration 2 & 3, and (c) Iteration 4

3.2.2 Fabrication of 3-D Printed Damper Connection Caps

The hand-drawn sketches for each iteration of the damper connection caps were then transformed into 3-D models in SolidWorks (similar to other design modelling software such as Rhino, but it is used more in industry). The program works off of reference planes to view each side of an object, including new planes created by the user. When modeling the caps, use of the two-dimensional plane system with commands like smart dimensions and mirror was beneficial. The extrude command made it possible to create the cylindrical cap in three dimensions, while the extrude cut command was used to create the penetrations in the cap for the damper and wood braces. To further optimize material efficiency of the cap design, chamfer and filet command were used to remove unnecessary material. Assistance with learning to model the connectors in SolidWorks was provided through tutorials by Austin McGee, a Project Engineer with a mechanical engineering background at Control Air Enterprises LLC.

The multiple damper connection cap design iterations are reflected in the 3-D printed products shown in Figure 11.

Figure 11. 3-D Printed Damper Connection Caps: Iterations 1, 2/3, and 4 (left to right)

Other than the use of four penetrations described in Section 3.2.1 that would allow reuse of the damper connection caps from Iteration 4, there was also efficiency gained by combining the set of caps to be printed in large batches as illustrated in Figure 12.

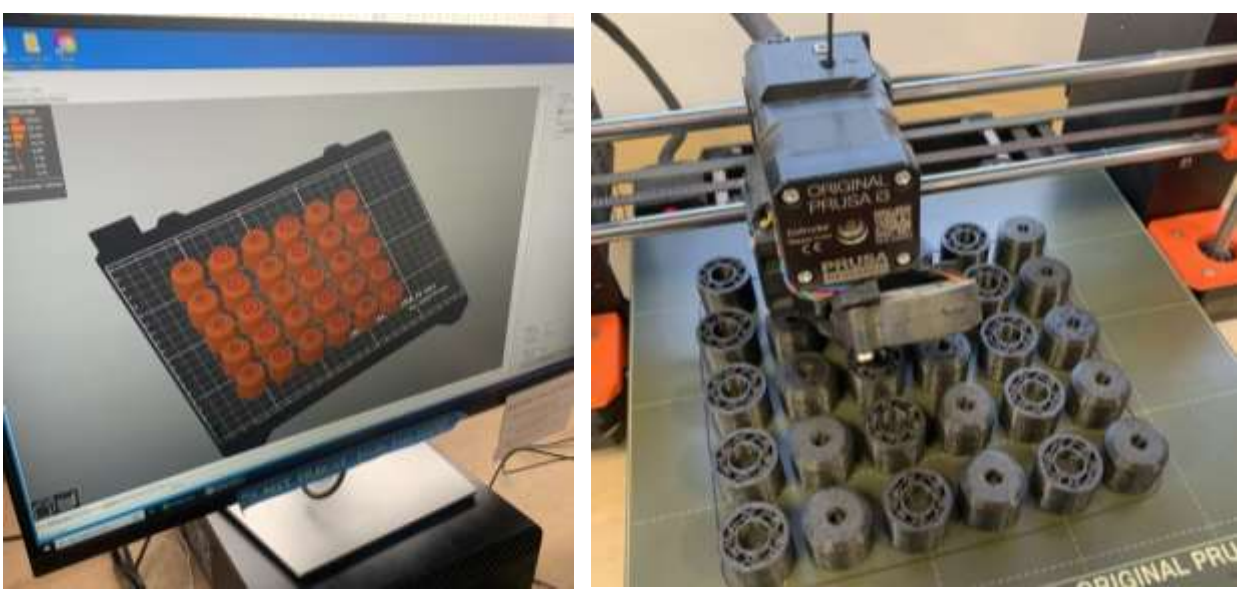

Figure 12. Large Batch 3-D Printing of Damper Connection Caps:
(a) Computer Input, (b) Product

The final design for the connection of the damper to the columns was the overall most efficient and sustainable design. Figure 13 shows the final damper with connection caps that was implemented into the competition structure.

Figure 13. Final Damper Assembly with Connection Caps

3.2.3 Design of Damper Extender Brace-to-Column Connection

The connection between the balsawood extender braces to the columns was a challenge and required several design iterations to achieve the best cut and fit given the damper placement and penetration through floor diaphragms as illustrated in Figure 14(a). The 19-story building contained 20 dampers that spanned the equivalent of two typical floor heights (6-in) from the ground level to the ninth floor. These dampers penetrated the diaphragm at a 45-degree angle through the interior space of the building. The orientation and placement of dampers can be referenced in Figure 14(b) and were chosen to abide by competition rules, keep the lateral force resisting system intact, and increase the effectiveness of the damper.

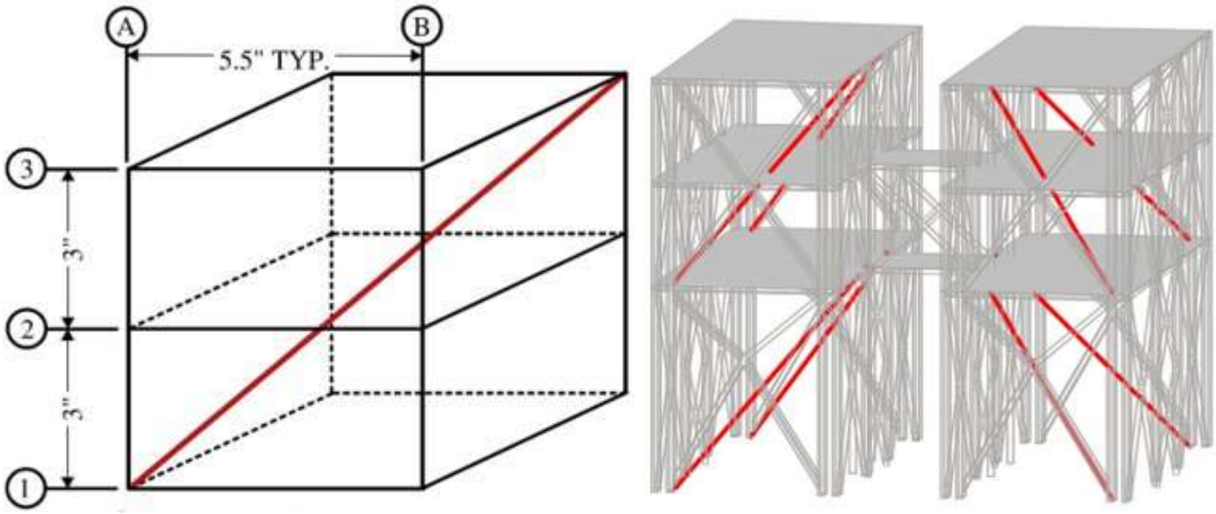

Figure 14. 3-D Damper Orientation and Placement:
(a) Dimensioned Drawing for Individual Damper, (b) Paired Dampers in Both Towers

The competition rules stated that during the day of the competition, dampers may be asked to be taken out due to rule violations. Per the Official Rules 2023 Section 7.7.c Rentable Floor Area, the rentable floor area must meet the requirements of at least one access point (i.e. doorway) with a width of 1 inch and height of 2.25 inches per floor. The damper design permitted sufficient room for an access point due to the available clearance being 2.75 inches wide and 3 inches tall as shown in Figure 15 (where the access points are shown outlined in red and the damper is the diagonal member in black). Since the same section of the rules indicates that framing members that penetrate the floor area are not subtracted from the rentable floor area, the decision to implement the dampers connected to framing members (i.e., extender brace) was advantageous.

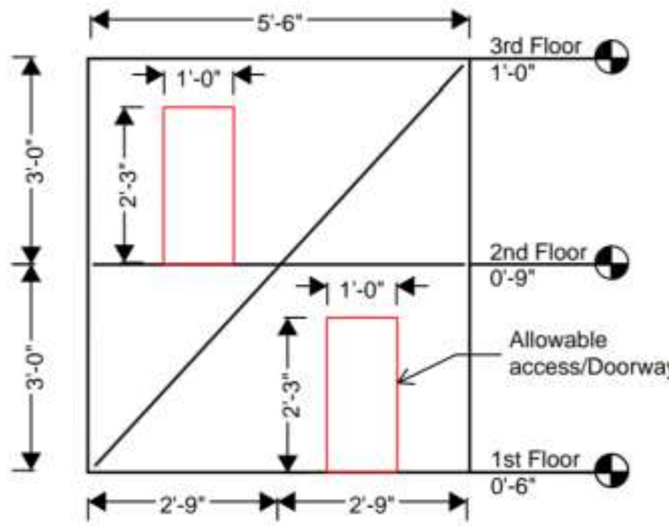

Figure 15. Damper Orientation for Access Point: Typical Section View (Floors 1-9)

To implement the dampers in the physical model, it was necessary to consider multiple iterations of different angle cuts for the braces to connect to the columns. The final design was 45-degree cuts to maximize the contact area between each brace to the respective column for the greatest faying surface to apply glue. Each brace connects to the interior face of two of the columns at the top connection. For the bottom connection, the braces only connect to a single column due to the interference of the spacers between the bundled columns. The sketches in Figure 16(a) illustrate how the angled ends of the extender brace connects at the top and bottom of the column, while Figure 16(b) shows the balsawood building model with the final extender brace-to-column design implemented (note that some the framing members have been hidden in this photograph so that it is easier to see the damper and the extender brace-to-column connection).

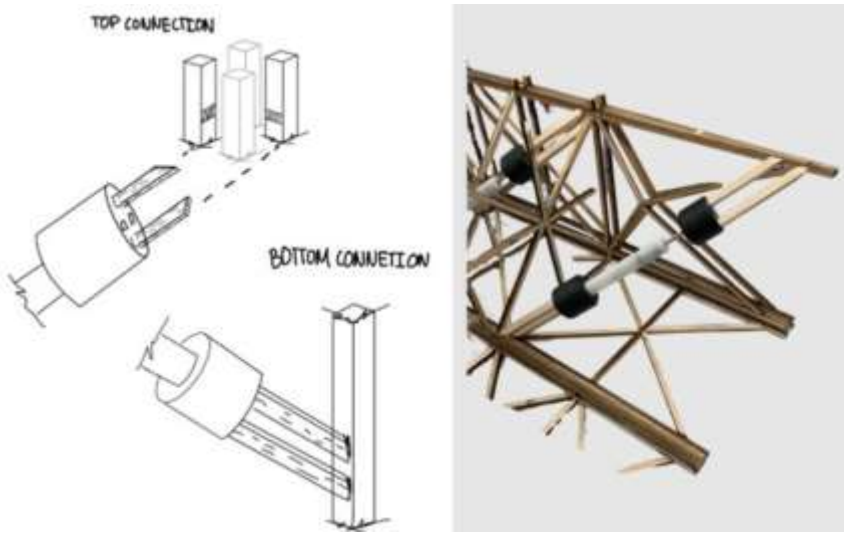

Figure 16. Brace-to-Column Connection: (a) Sketches, (b) Physical Model

3.2.4 Final Damper Configuration in Competition Model

Figure 17 and 18 shows images of the final competition model with close-ups of the damper system to better understand the diaphragm penetration and brace-to-column connections.

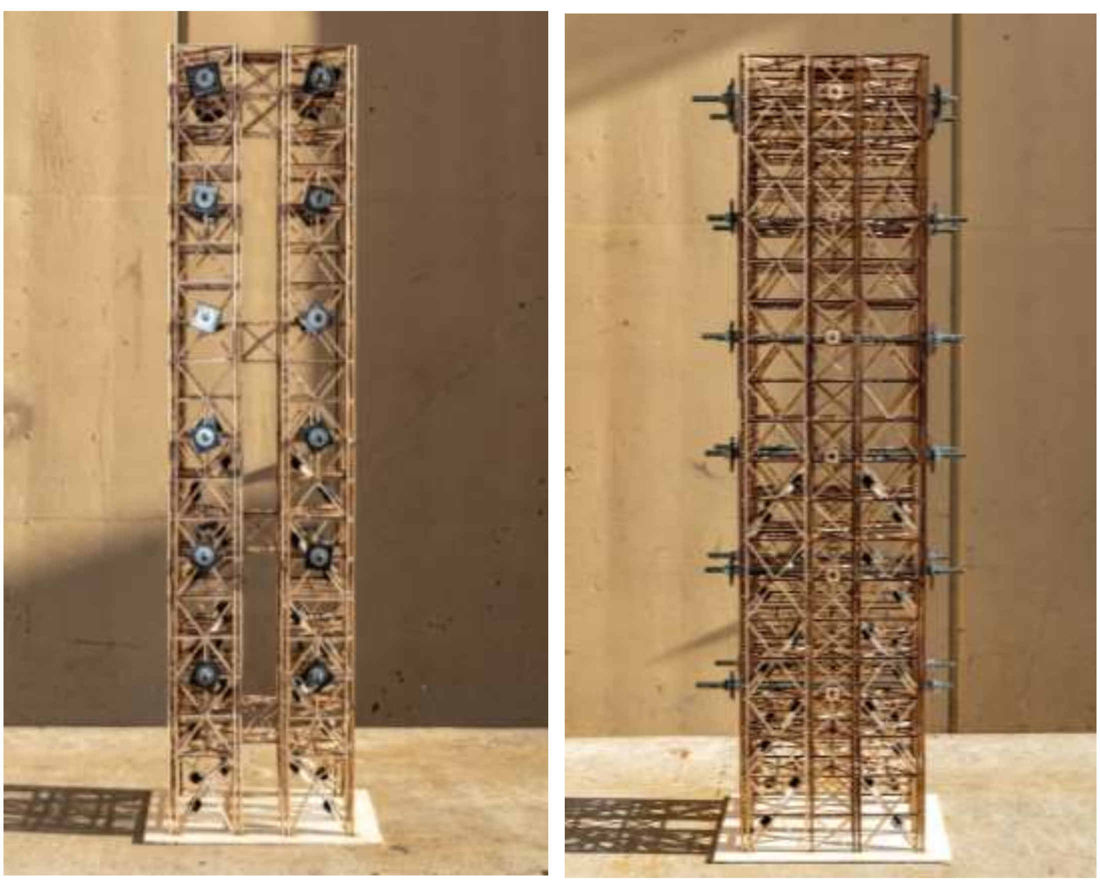

Figure 17. Final Competition Model: (a) North Elevation, (b) East Elevation

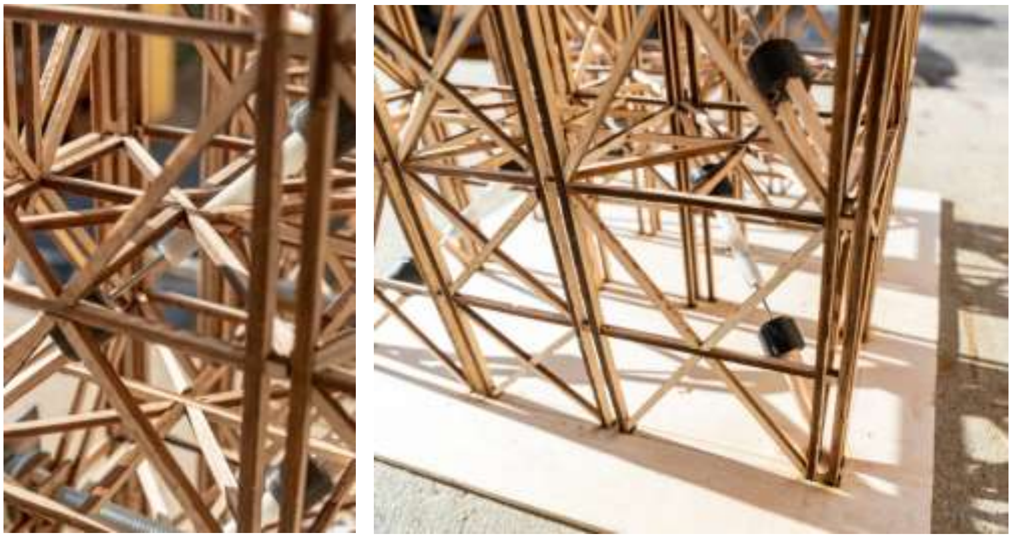

Figure 18. Final Competition Model Details:
(a) Damper through Diaphragm Penetration, (b) Brace-to-Column Connection

4.0 Testing to Characterize Damper Properties

A significant scoring component in the EERI SDC competition is based upon the accuracy of a team's roof displacement and acceleration predictions of their building for shake table testing with two ground motions. Teams use structural analysis software such as ETABS or SAP2000 to analyze their mid-rise balsawood model to help develop these predictions, in addition to running preliminary shake table tests on a prototype model.

Both the physical construction and ETABS modeling for the 2023 Cal Poly team would be unique because of the desire to implement fluid viscous dampers into the structure. The team was motivated to add dampers both to earn the associated bonus points and to improve the response of the dual narrow towers being joined by skybridges, but this would require adapting past year's ETABS modeling approaches to reflect a supplementary damping system which had not been done before. The only way it would be able to account for the specific dampers in the model with any level of accuracy was to conduct physical testing of the dampers to characterize their dynamics properties and compute a damping coefficient to then input into the ETABS model.

4.1 Equipment

4.1.1 Damper Test Structure

Ideally, the team would have a full-scale replica of the competition model to test with and without dampers to fully characterize the effect on the building displacements and accelerations. Given the unrealistic amount of time and cost that such a task would take, the team had to turn to a smaller scale model in the form of a multi-degree of freedom (MDOF) steel structure shown in Figure 19(a) that was available in the Cal Poly Architectural Engineering Seismic Lab.

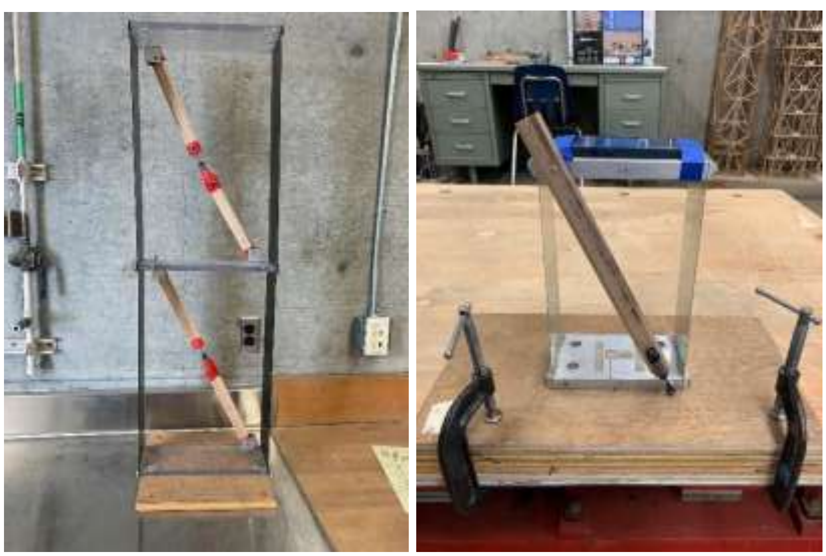

Figure 19. Damper Test Specimen: (a)MDOF Model, (b) SDOF Model

The team attempted to attach the test damper in the center of the spans of each story. The damper had a fixed connection to each of the wooden braces framing into the story below and above, while the braces had a pinned connection with the joints into which they were framed. Due to the multiple degrees of freedom of the structure as well as the damper configuration, this model introduced a lot of variability in the forced vibration testing results that needed to be reduced as much as possible to accurately characterize the damper.

Ultimately, the damper test structure used to collect test data was a single degree of freedom (SDOF) system shown in Figure 19(b) with the damper framed directly into one corner of the structure. There still was a wooden brace fixed to the damper with pinned connections at each of the corners. Because of this, the variability was greatly reduced since the damper only connected to one wooden brace. A SDOF structure also allowed for a more direct characterization of the damper, as opposed to the response of the MDOF structure.

4.1.2 Uni-Directional Shake Table

The process of conducting forced vibration testing required the use of the large uni-directional shake table that operates using a hydraulic actuator in the Cal Poly Architectural Engineering Seismic Lab shown in Figure 20(a). Rather than the two simulated earthquake ground motions for the competition, the team used sinusoidal input at various frequencies to conduct a frequency sweep that could be used to characterize the effect of the damper. This shake table is capable of precise input motions and it is easy to manipulate the frequency and amplitude for the forced vibration tests. Specifically, the shake table can achieve frequencies of 0-15 Hz at a displacement range of +/- 2.5 inches and an acceleration accuracy of +/- 5% [12].

Figure 20. Uni-Directional Shake Table: (a) Platen, (b) Control Panel

To conduct multiple frequency sweeps of the damper test structure on the shake table, the team used the control panel shown in Figure 20(b) to change the frequency (Hz) and amplitude for the sine wave input (rather than approach when simulating ground motions where the table is controlled via an input file on a desktop computer). The amplitude was set to a sufficiently large magnitude so the SDOF structure would experience visible motion, but avoid yielding of thin steel frame. This amplitude was set at the beginning of the forced vibration test and kept constant for the remainder of the sweep to insure consistency and that the measured response of the structure was based only on frequency change.

As a note for readers who are future Cal Poly EERI SDC team members, there is a smaller uni-directional Quanser shake table available in the Cal Poly Architectural Engineering Seismic Lab that was available to the team but not utilized for the purposes of damper characterization. This screw-based shake table provides less accuracy in the sine waves that it produces. It is also harder to control the frequency and amplitude once the shake table is already running, which makes the execution of frequency sweeps difficult since that process relies heavily upon switching between frequencies in order to determine the resonant frequency. It is therefore recommended that the large uni-directional shake table is utilized for future studies of this type.

4.1.3 Instrumentation & Data Acquisition

The primary sensor type that was utilized were PCB Piezotronics Model 393B04 which are uniaxial accelerometers with a sensitivity of 1000 mV/g and can measure frequencies of 0.06 to 450 Hz [13]. The accelerometers were mounted to an aluminum L-shaped bracket. During the testing of the SDOF structure one accelerometer was clamped to the top story of the structure, this would measure the acceleration that would be used to assess the change in the frame structure's dynamic properties with and without the damper. Another accelerometer was attached to the shake table platen to ensure the accuracy of the input motion to the shake table. A coaxial cable from each accelerometer connected to a channel on the National Instruments CompactDAQ 4-slot chassis (NI cDAQ-9174) with a single 4-channel module (NI 9234) that could collect data. The chassis was connected to a laptop computer with NI SignalExpress software that was set up to utilize a Butterworth filter and remove low <1 Hz ad high >20 Hz frequencies. In the SignalExpress display it was possible to view the acceleration time history and the Fourier transform to examine the maximum acceleration amplitude with corresponding resonant frequency. The accelerometers, NI CompactDAQ, and laptop are shown in Figure 21.

Figure 21. Instrumentation: (a) Accelerometers, (b) NI CompactDAQ, (c) Laptop

4.2 Damper Test Set-Up & Data Collection

4.2.1 Forced Vibration Data Collection

For the initial method of characterizing the dynamic properties of the damper from Section 2.2, the team conducted forced vibration test. The goal with this method of testing was to produce a frequency sweep curve and use the half-power bandwidth method to compute the damping coefficient [14]. The test set-up consisted of two PCB 393B04 accelerometers attached to the SDOF structure at the top story as well as fixed to the shake table. The SDOF structure was also clamped to the shake table. To conduct the test, one person would operate the shake table control panel setting the amplitude and frequency of the sine function, while another would operate the data acquisition laptop computer to review and record acceleration time history and Fourier transform results.

The first step in testing was to find the resonant frequency and corresponding amplitude of the baseline SDOF structure without the damper attached (inherent damping only). This method of testing used a "ping-pong" style of narrowing down the precise resonant frequency of the structure. This involved running the shake table starting at a low frequency, and then increasing the frequency by 1 Hz increments while the observed acceleration amplitudes increased. Once there was a noticeable decrease in acceleration amplitude, the input frequency was reduced to a 0.1 Hz step size to scan nearby frequences for another peak, this process was repeated until the resonant frequency had been determined with a precision of 0.01 Hz. Once this was determined it was also necessary to run the structure through increasing and decreasing frequencies away from the resonant frequency to collect data at "target frequencies" for the half-power bandwidth method where values are $1/\sqrt{2} \times$ resonant amplitude. Having determined this information for the undamped structure, the damper was attached to the SDOF structure and another frequency sweep was conducted to determine the new values with this supplementary damping system. The results from these two frequency systems are shown in Figure 22.

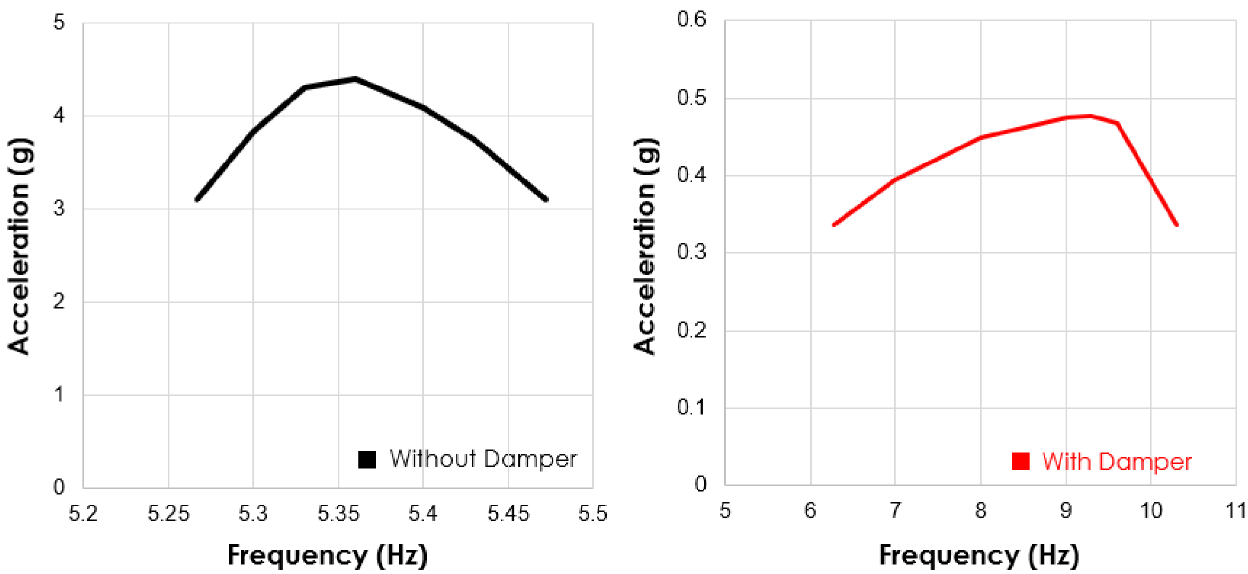

Figure 22. Forced Vibration Response of SDOF Structure With and Without Damper

Through this experimentation it was clear that the damper was very effective in decreasing acceleration amplitude and that the resonant frequency had experienced an upwards shift, indicating that the period had decreased and therefore that the SDOF structure's stiffness had increased. This finding meant that the dampers behaved in a viscoelastic rather than viscous manner.

4.2.2 Free Vibration Data Collection

For the free vibration testing, the SDOF structure was clamped at the base in order to keep it stationary and only one accelerometer at the top story of the structure was utilized, otherwise all other test set-up was the same as the forced vibration test. To start the test, the top story of the structure was manually displaced by 1-in and released from rest so the structure would undergo free vibration. For the SDOF structure without the damper attached, the top story would oscillate for an extended period of time and data collection was usually terminated after about 30 seconds although the structure was still moving since there was sufficient data at that point. The same process was used for the SDOF structure with damper attached, and there were drastically different results. The dampers were very effective; therefore, the structure would, when released from a 1-in displacement, return to rest very quickly with few oscillations. The graph in Figure 23 shows the acceleration time history for the SDOF structure with and without the damper.

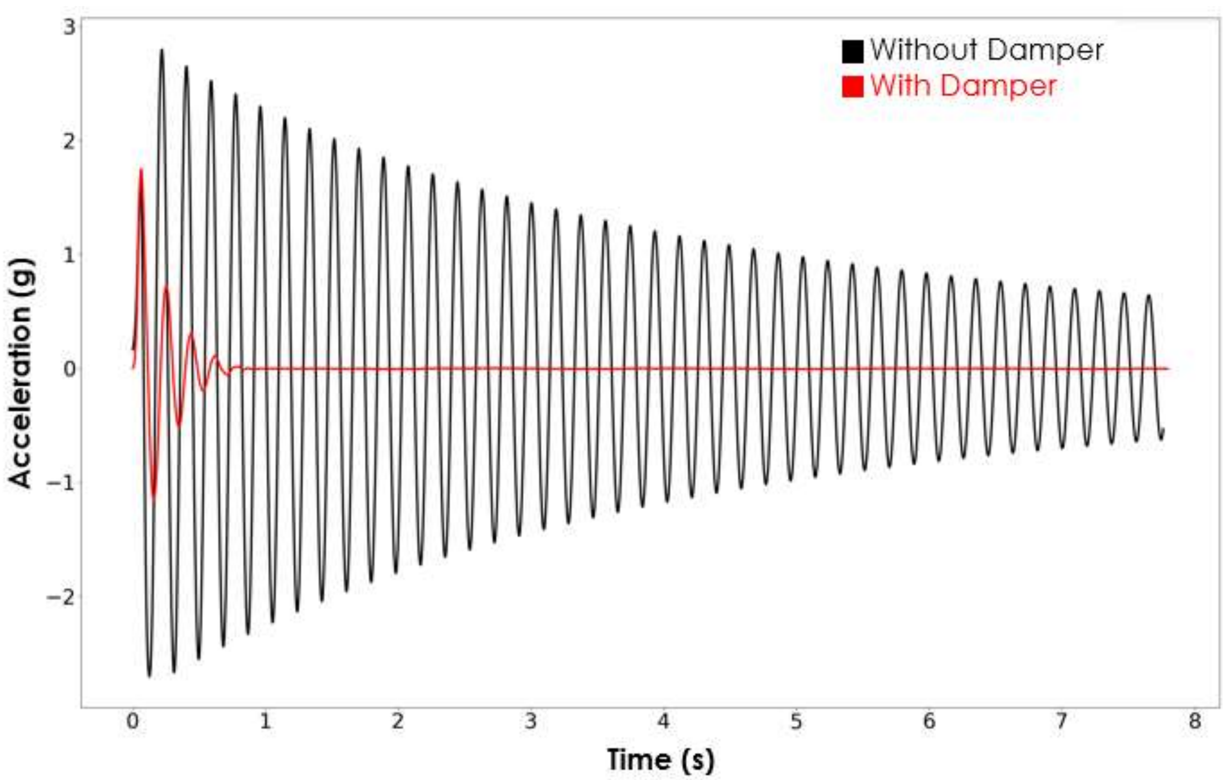

Figure 23. Free Vibration Response of SDOF Structure With and Without Damper

The team used the logarithmic-decrement method to determine the damping ratio for both free vibration tests which takes the rate at which the amplitudes of the acceleration decrease over a specified number of peaks [14]. The difference between the damping ratios allows for the effect of the damper to be characterized which can then be used to calculate the appropriate damping coefficient to input into the ETABS model for competition. The damping ratio determined for the damped configuration was approximately 15%.

As a note, the ETABS modelling was conducted by other Cal Poly EERI SDC team members and not part of the defined scope for this senior project that was focused on developing the proposal for, selecting or designing, characterizing, and then successfully implementing the dampers in the physical balsawood prototype and competition models.

5.0 Building Model Response

5.1 Prototype Building Model Testing

Physical testing of the prototype balsawood model with the dampers was important to determine the maximum roof acceleration and displacement values for the competition ground motions to calibrate the ETABS model and to incorporate into the predictions submitted as a competition deliverable. Figure 24 shows the acceleration time history for the prototype structure subjected to the two earthquake ground motions. Qualitative observations of damage from these tests were also valuable to inform design and construction changes to the final competition model.

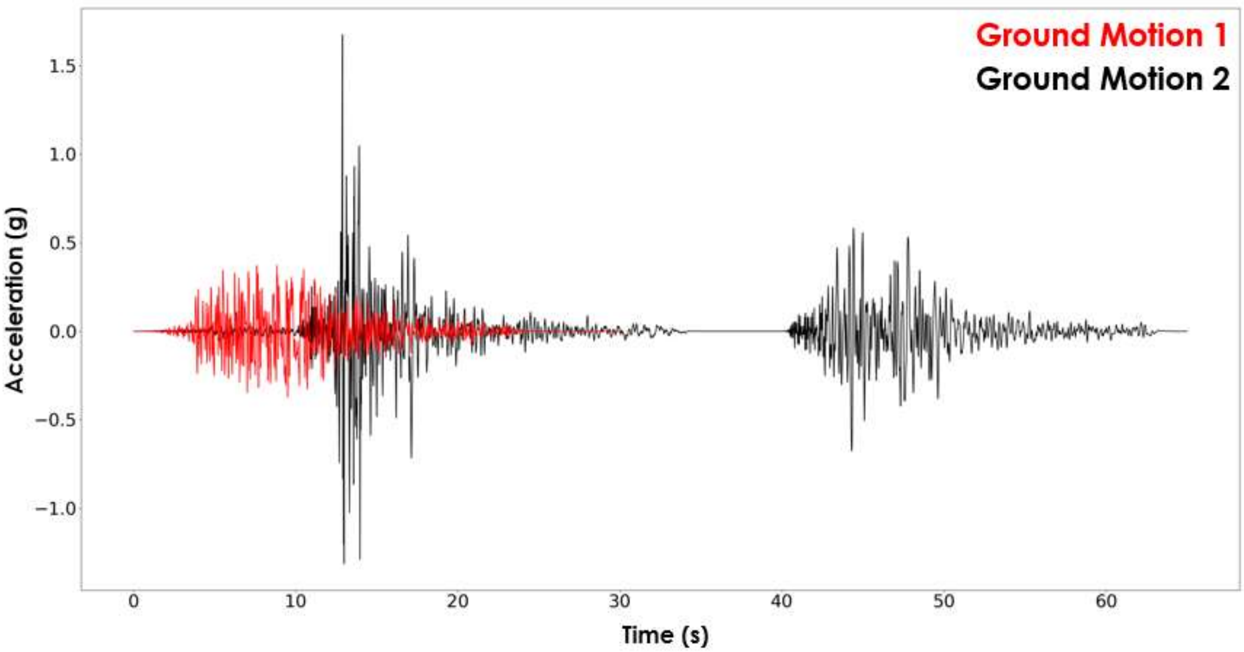

Figure 24. Prototype Building Response to Ground Motions 1 & 2

5.2 Competition Building Model Performance

The competition planning committee decided to shake the building in the East-West direction. Figure 25 shows a comparison of the predicted values that the Cal Poly EERI SDC team submitted prior to the competition (top row) to the actual values recorded at the competition (bottom row), where there is quite a large discrepancy particularly in Ground Motion 2 which can be attributed to two major issues. First, the prototype building used to calibrate the ETABS model had construction issues including the wood members being cut against the grain, while this issue was corrected for the competition model so the stiffness and strength of the members was likely different. The second issue was that the competition model endured significant damage during the second earthquake ground motion, which was not observed in shake table testing of the prototype model and therefore not accounted for in the ETABS model. Related to that, the ETABS model that the Cal Poly EERI SDC team has always been conducted as a linear time history analysis, so it does not account for damage to members during the ground motion.

East/West Shaking	
Ground Motion 1	
Acceleration (g)	Displacement (in)
1.204	0.134
1.31	0.4
Ground Motion 2	
Acceleration (g)	Displacement (in)
4.56	0.415
2.56	1.91

Figure 25. Competition Building Model Performance vs. Predictions

The 2023 Cal Poly EERI SDC team placed 11th out of 24 teams, specifically receiving high marks in the Architecture and Final Annual Seismic Cost scores.

5.3 Lessons Learned from Building Model Response

There are valuable insights to be gained from both the prototype and competition model's shake table performance. First, ensuring an adequate penetration depth of the ground floor columns into the base plate is vital (and adequate base plate thickness), as this would have prevented many of these columns from pulling out. Creating a bevel from the bottom of the hole could prevent the glue in these base plate penetrations from pulling out. The failure of the column base connections resulted in load redistribution that led to increase in force in the ground floor braces which subsequently failed as well. Another observation was that offsetting the lap splices along the column heights would have prevented them from fracturing along a horizontal plane and avoided what was nearly an overall failure in the building. Lastly, all balsawood sheets should be laser cut with the grain parallel to the length of the structural members with consideration for the strong versus weak direction of behavior for wood. Incorrectly cut members will render them unusable for constructing a resilient building model. Figure 26 illustrates these failure types.

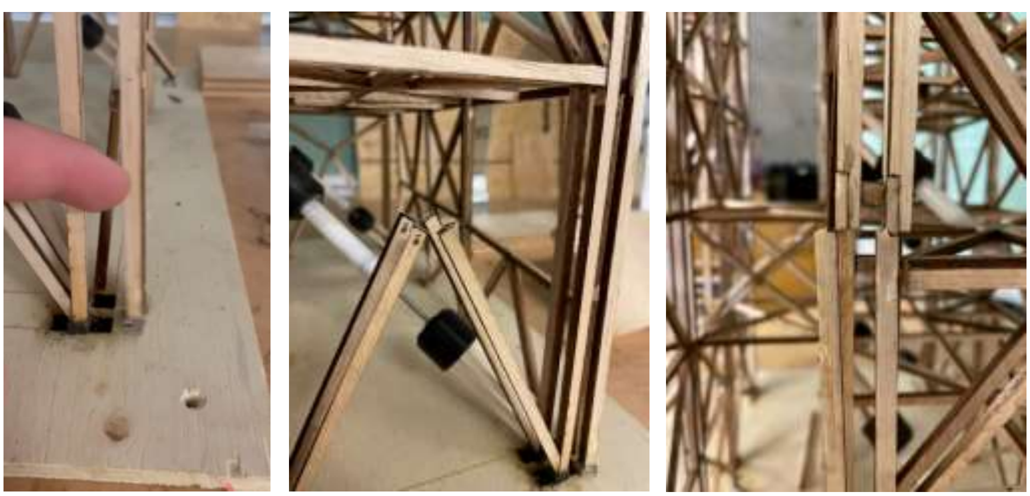

Figure 26. Competition Building Model Issues: (a) Insufficient Penetration Depth for Base Columns, (b) Load Redistribution Resulted in Brace Failure, (c) Column Splices Not Staggered

6.0 Conclusion

6.1 Establishing Precedent for Using Dampers

Due to all the benefits provided by damping systems that have been stated previously in this report, future EERI SDC teams may want to pursue damping as an option and the authors suggest the following process. First, determine the possible locations for dampers. Since their purpose is to dissipate energy, identify areas expected to experience of high relative deformation. Next, choose a damper that works with the structural system and achieves the desired performance. There are many types of dampers but the main ones that are viable for the competition are fluid viscous, fluid viscoelastic, friction, and rocking wall systems. Each comes with its own benefits and drawbacks (see the brief descriptions in Section 2), so choose one that works with the building's design. Note improper selection of damper type or installation can increase the building's stiffness, thus increasing acceleration which leads to greater forces and increased potential of damage in structural members. Finally, test the selected damper using the methods described in Section 4. These help characterize the dynamic properties of the damper for ETABS modelling and also to ensure that the dampers will work as intended within the balsawood building model.

Other aspects to consider when implementing dampers is determining the optimal start date for the prototype and competition model construction, which can vary depending on the competition date and the complexity of the build. For effective planning, it is recommended that Section 2.2 of Robinson [1] be reviewed as it contains a table describing the competition timeline that can be customized to suit each team's specific schedule. However, this example schedule does not include time for designing and implementing dampers. From the time that the authors began investigating damping approaches for the proposal to having the damper, connection caps, and brace-to-column connections completed was almost 2.5-3 months. Within that the time frame the portion from initially placing the damper order to receiving the correct items was nearly a month. Some dampers may be in short supply or difficult to acquire, so sourcing them as soon as possible would alleviate delays in the overall model construction process. On that topic, the same approach should be taken for other building materials. The balsawood order year-to-year has been relatively consistent in type and quantity for the Cal Poly EERI SDC team irrespective of the specific building design; therefore, it is highly recommended that the wood be purchased before the end of fall quarter even if the building design is not yet complete.

6.2 Potential Impact of Dampers as an Earthquake Engineering Solution

6.2.1 Economic Considerations

The implementation of dampers into buildings today has been shown to have a positive impact on a building's economy. The fluid viscous damper allows energy to dissipate, therefore resulting in less structural damage during an earthquake. Furthermore, the dampers help reduce deflections, keeping the building in the elastic range which allows for a repair cost reduction and exceed a minimum the life safety performance objective [2]. This means that the building may perform sufficiently well to have immediate occupancy after an earthquake unlike other neighboring buildings which would face more damage and a threat to life safety. Another benefit to adding dampers is that it increases the lifespan of the building; therefore, the client gets more revenue before a retrofit is needed. As an example. the lifespan can be up to 50-plus years when using a fluid viscous damper provided by Taylor Devices with no maintenance required [2]. Lastly, the implementation of dampers allows for the designer to design the structural system with greater material efficiency. As previously mentioned, the damper dissipates energy, therefore reducing stresses to the structural elements. This allows for the reduction in member sizes as well as using a less complex foundation because the structural elements are subjected to less force generated by the earthquake lateral loading [2]. In summary, the economic benefits of dampers are that they improve the building's structural resiliency which in turn has a positive impact on occupant life safety along with significant cost reductions for both the original construction and post-earthquake repair of the building.

6.2.2 Societal & Global Considerations

During the 2023 EERI Annual Meeting and Competition, the Cal Poly EERI SDC team attended a special session to learn from professionals and researchers who had just returned from conducting geotechnical, structural, and civil infrastructure reconnaissance after the devastating earthquake that effected Turkey and Northern Syria. This is a high seismic area in the Mediterranean which endured two fault line ruptures that created significant earthquakes in early 2023, measuring 7.8 and 7.5 in magnitude [15]. These earthquakes inflicted immense damage: the collapse of approximately 3,450 buildings and the loss of life and displacement of thousands [16]. Poor building practices were described as what led to a higher death toll and increased destruction that displaced many Turkish people and created its own humanitarian concerns. Shockingly, many buildings were not constructed to meet safety codes and there have been allegations that this may be due to contractors taking shortcuts or bribing officials to approve substandard projects [17].

Another concerning issue of the Turkey earthquakes was the damage and destruction of critical facilities like hospitals and schools, which are pivotal in post-disaster recovery. The integration of damping technologies similar to those we have explored could mitigate earthquake impacts and ensure continued accessibility during crises. The Turkey earthquakes have brought fear and distrust among the public that will last generations and serve as a reminder of the role of structural engineering and the opportunity to implement new technology.

Buildings that were constructed according to code demonstrated better resilience during the earthquake. Furthermore, structures equipped with dampers and base isolation systems performed as intended, significantly reducing damage and enhancing overall safety. These positive examples emphasize the importance of following proper building practices and incorporating innovative technologies into construction processes.

The tragic consequences of cutting corners were felt by thousands who lost their lives and homes. During the EERI conference, the speakers' first-hand accounts underscored the critical role of structural engineers and the construction industry. Their work in prioritizing safety, adhering to codes, and embracing technological advancements is fundamental to safeguarding communities from the destructive forces of natural disasters. Listening to these presentations served as a stark reminder of the responsibility and significance of the earthquake engineering profession in shaping resilient and secure environments for future generations.

6.2.4 Cultural Considerations

The implementation of damping systems in structures can ensure the existence and protection of culturally significant buildings. An example of this is the base isolation system, a type of friction pendulum damping system, implemented in the design of the Cathedral of Our Lady of the Angels in downtown Los Angeles (shown in Figure 27). According to the lead seismic engineer, Nabih Youseff, this structure was intended to serve as a functional church during the week and a refuge for the displaced during a crisis, such as a devastating earthquake. This could only be accomplished by implementing a base isolation system which helped to reduce the shaking in the structure to approximately ¼ of what it would have been with no damping system in place. Due to innovation and engineering of base isolation systems, this culturally significant structure will theoretically be able to remain functional throughout its 500-year lifespan [18]. Beyond this cathedral, there are many culturally significant structures today that implement damping systems. Moving forward, with more research and innovation, hopefully these damping systems will become more widely accessible so that cultural structures of all sizes and importance can benefit from the implementation of these systems.

Figure 27: Cathedral of Our Lady of the Angels

6.2.5 Environmental Considerations

Prioritizing an efficient structural design minimizes member sizes which reduces the environmental impact of construction. This goal was achieved through several approaches in the Cal Poly EERI SDC competition structure. Instead of opting for a simpler grid system, a more complex diaphragm system was developed to distribute loads effectively while also saving materials. Although this decision required additional time and effort, it was deemed the most effective way to decrease the structure's overall weight and quantity of materials used.

Sustainability through materials and environmentally conscious design is only effective if a structure is also resilient. Recognizing that resiliency is a key element of sustainability, the implementation of dampers can help prevent damage in high seismic events. In turn, the building is less likely to be damaged and ensures a quicker recovery and restoration of building functionality.

Combining these eco-conscious strategies actively lessen the environmental footprint and demonstrates a commitment to building structures that can withstand the dynamic loading during the competition. This approach aligns with the Cal Poly team's vision for creating a sustainable future and emphasizes the significance of responsible design and construction practices in preserving the planet's resources.

6.3 Student Reflections on Lessons Learning

6.3.1 Tynan's Personal Reflection

The 2022-2023 school year was my first experience with the Earthquake Engineering Research Institute club at Cal Poly. The 2023 Seismic Design Competition in San Francisco was also my first time at the competition in person. I was able to learn from every step of the process as a part of this club, gaining new skills as well as sharpening old ones.

One task that I was given that I did not have prior experience with was the operation of the shake table and subsequent data collection of our model. As previously discussed, one very important portion of our senior project was the testing of our damper to obtain a damping coefficient for our ETABS model. The damping coefficient was very important because that would allow us to have accurate predictions for our building's displacement and acceleration on the shake table. One crucial part of testing was learning how to run the shake table to perform a frequency sweep for our forced vibration testing. Running the shake table required precision and communication to produce viable data. Similarly, we needed to learn how to properly use the accelerometers and computer for both free and forced vibration testing. This process of collecting data required consistent methodology and knowledge of our equipment. I was also part of the process of 3D printing our custom designed damper connections. In addition to learning patience, I also learned how to use the 3D printing machines and how to optimize our time spent on the machines and in the lab.

Both my experience with the EERI team as well as my time at the competition proved extremely valuable in helping me hone soft skills necessary to being a successful engineer. Coordination and communication were extremely important, not only with the large scale EERI team, but also with our smaller senior project team. Learning when I needed to take charge as well as when I should provide support were vital to helping the team run as smoothly as possible. There were a multitude of learning opportunities at the competition as well. Speaking with other teams and taking note of other schools' design processes helped tremendously with how we might look forward to future years' competition. Recognizing where we made mistakes and how we could learn from them are key to being a good engineer and leader.

6.3.2 Payton F.'s Personal Reflection

This was my second year as a member of the EERI Seismic Design Team and my first year as co-captain. I can confidently say that I have never been more challenged, excited, frustrated yet hopeful, and proud as I have been through this experience. Through the last two years I have gained invaluable experience that has enriched my knowledge, honed my skills, and provided me with a deep appreciation for the intricacies of structural engineering. This competition allowed me to apply classroom theories to real-world scenarios, pushing me to think creatively, collaborate effectively, and problem-solve in a dynamic environment.

Being a leader is not something I am accustomed to and yet I decided to take on that responsibility this year. Through my role as co-captain, I not only grew as a technical professional but also as a leader, learning to guide my team while navigating unforeseen challenges. Team management is a paramount skill as there is little progress with no collaboration.

This experience has fostered new relationships with peers from all over the world as I discovered how different countries and differing cultures approach the problems of and within structural engineering every day. Speaking with peers from other countries like Romania and India, as well as peers from my own backyard like Cal Poly Pomona, I have been given a wider worldview fit with a more robust understanding of the challenges facing our world and industry. This understanding was further strengthened as our team had the privilege to listen to a presentation about the Turkey Earthquakes and the many confounding variables that contributed to this crisis. This presentation gave me more awareness of the many issues outside structural engineering that contribute to the collapse of buildings, like corruption and poor building standards, which important problems to address in the world before another devastating earthquake.

In addition to other responsibilities, I was tasked with understanding and reporting on the geological conditions and seismicity of the chosen location. This year was San Francisco, a notoriously seismically complex area with multiple overlapping conditions that affect the behavior of the earthquakes felt in the Bay Area. I had prior knowledge gained through courses taught at Cal Poly SLO about geology and earthquakes which helped point me in the right direction, however, I needed to learn how to research a topic with little prior information. This led me to learn about seismic deaggregation plots and hazard maps which help illustrate the severity of potential earthquakes and the likelihood of danger to those living close to fault lines. I also learned through this task about the way different types of soil will change the amplitude and frequency of earthquakes as they pass through. Understanding these effects helped me to better understand the behavior of the earthquakes reaching the location.

Overall, this experience solidified my commitment to the field of seismic engineering and has given me the confidence to continue contributing to the advancement of earthquake-resistant designs. I am grateful for the opportunity and look forward to applying the lessons learned from the EERI SDC competition in my future endeavors as I strive to make a meaningful impact in the world of structural engineering.

6.3.3 Payton M.'s Personal Reflection

This was my first year joining the Earthquake Engineering Research Institute organization and competing in their Seismic Design Competition. While designing and analyzing a structural model for the competition was a learning curve, implementing dampers added more to my learning experience.

My role on the senior project team was to design and fabricate the caps that would connect the dampers to the structural system of our mid-rise building. This was a new challenge and with the help of an industry professional I was able to reach our goals. Through many Zoom meetings, I was able to learn a new program called SolidWorks that enabled me to convert my 2D design sketches of our cap connections into 3D models that could be exported to an STL file for 3D printing. In addition, I learned how to use a 3D printer, which was an iterative process that required patience to troubleshoot issues like printer alignment or recognizing task files, often with the help of the student CAED shop staff. Time management was also critical to producing all forty caps done before competition. Therefore, making a deadline and schedule was key for our senior project group and the EERI team.

Being a part of the Cal Poly EERI SDC team improved our time management, collaboration, and communication skills. We created time sheets to schedule team members around their academic/work needs. Although it became a little overwhelming at times, especially during our final's week, we all put in our best effort to create a competition model, poster, and presentation. At the competition, we were able to learn about the 2023 Turkey Earthquakes from the EERI Learning from Earthquakes teams which data had not been publicly presented on yet. This was a great learning experience for us because we got to understand how much we as structural engineers can help after a seismic event. We can conduct reconnaissance, help with repair or rebuilding, or tag buildings that are unsafe and cannot be occupied. Previously, I thought only outreach and non-profits did this, but now I am aware that many structural engineering companies have these programs to help.

I got to how to learn how to conduct forced vibration tests on the large shake table in the CAED Seismic Lab as well as free vibration tests. I learned why it was valuable to check the differences we got for our damping ratios because sometimes the shake table cannot give you the most accurate data. Finally, I got to understand the mechanics and functionality of a fluid viscous damper. Although the damper experienced a viscoelastic behavior, we got to investigate why this was the behavior by performance of our building.

Overall, the competition gave me valuable lessons that can be taken into my professional career. Being able to understand the importance of implementing dampers into a structure that is in a high seismic area is crucial to prevent harm to human life. With examples such as the Turkey earthquake and many more we are able to understand the importance of these systems. I hope in the future I am able to carry these lessons learned into my professional career in order to educate others for the public good.

6.3.4 Dalton's Personal Reflection

Reflecting on my second year as a member of the EERI team and my first year as a captain, I am filled with a sense of growth and accomplishment. This journey has been transformative, and I have improved my structural engineering knowledge and leadership skills.

Being part of the EERI team has provided me with invaluable hands-on experience and exposure to real-world challenges. Working closely with teammates and seasoned engineers and participating in various projects allowed me to deepen my understanding of structural analysis, design principles, and seismic-resistant technologies. I found myself diving into complex structural problems more confidently and finding innovative solutions through collaboration and research. As a result, my technical expertise has grown significantly, and I now feel more adept at tackling intricate engineering challenges.

Taking on the role of captain was a whole new endeavor for me, and it presented a steep learning curve. I had to step up as a leader, inspiring and guiding my team members to perform at their best. Motivating others, building consensus, and fostering a positive team spirit was rewarding and challenging. Throughout the year, I improved my communication skills, learning to listen actively, delegate tasks effectively, and provide constructive feedback. I also became more adept at managing conflicts and finding solutions for the team.

One of the most significant areas of growth for me was adaptability and resilience. As a captain, I faced unexpected obstacles and had to adjust our plans accordingly. Learning to remain calm and flexible in the face of uncertainties has been crucial in keeping the team on track.

Moreover, my experience as a captain allowed me to recognize the importance of mentorship. I took the opportunity to support and nurture the newer members, just as I had been guided when I joined the team. Witnessing their growth and enthusiasm has been incredibly fulfilling.

Overall, my second year on the EERI team and my first year as a captain has been a profound and enriching experience. I feel more passionate and dedicated to structural engineering than ever before. The combination of technical knowledge and leadership skills I have gained will undoubtedly shape my future career. I am excited to continue contributing to the field's advancements while nurturing the next generation of engineers.

6.4 Final Remarks

In addition to the many lessons mentioned in the personal reflections, each member of this team gained invaluable insight, such as an emphasis on innovation within seismic engineering and a greater understanding of the architectural and social importance of a structure.

The annual EERI Seismic Design Competition challenges students from around the globe to innovate, collaborate, and showcase their geological, structural, and architectural ingenuity. This year's team was asked to perform the intricate task of designing two narrow towers, joined by sky bridges, while seamlessly blending both traditional and modern elements of the San Francisco skyline. The aptly named "Lucid Tower" not only captures the architectural blend of the SF skyline, but also answers the city's call for sustainability, transparency, and progress.

Central to the endeavor was the decision to introduce a damping system into the tower's design. The pursuit of a more resilient, lightweight, and sustainable structure drove the team to explore the potential of damping systems, a territory previously uncharted in Cal Poly's history. This report stands as a valuable resource, delving into the methodologies, lessons, and experiences gleaned from the 2023 EERI SDC journey.

7. References

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Appendix A. Damping Proposal Requirements and Submission

A.1 Damping Device Approval Process

6. Design Proposals and Damping Device Approval Process

6.1 Design Proposals

Your team is required to submit a proposal for evaluation by the SDC Chairs. Invitation to participate in the competition will be determined by the proposal score. If a team fails to submit their proposal by the deadline, they will not be invited to participate in the competition. The number of accepted teams will be based on time limitations and space availability at the conference venue. No funding will be offered to teams for their proposals—instead, funds will be used to improve the quality of the venue and activities that benefit all attendees. A bonus score multiplier will be awarded to the nine best proposals (Section 4.1.e). Teams must follow the instructions and guidelines for the proposal that are provided in the Proposal Requirements document on the competition website.

6.2 Damping Device Approval Process

All proposed damping devices shall be subjected to the approval process. A separate PDF document shall be submitted to sdc@eeri.org. The requirements of the damper proposal can be found on the competition website. **This year, the accepted damping proposals will be eligible to be awarded a bonus up to 9% (Section 4.1.d)**. The date of the submission of the damping device proposal will be announced on the competition website. Proposed damping device must be described in detail, explaining the materials used and the device's placement(s) within the structural model. Figures are highly recommended to aid in describing the damping device.

The SDC Chairs evaluation of the proposal will be based on the rubric that can be found in the Damper Proposal Requirements document. Approved damping devices are required to be used in the submitted structural model at the competition and will be checked by the SDC Chairs prior to the competition. However, if a damping proposal is not submitted or rejected, then damping devices may not be used.

The criteria used by the judges to approve a damping system are as follows:

- If the damping system is removed, the balsa wood structure, with all dead load weights attached, should be stable and firmly fixed to the base plate.
- The primary purpose of the pre-approved damping devices is to dissipate energy.
- Base or floor isolation of any kind is prohibited.
- The proposal meets all the guidelines that are provided in the Damping Device Proposal Requirements on the competition website.

2023 Undergraduate Seismic Design Competition – Rules 27

General notes:

- Damping devices may be attached to the base plate.
- All damping devices should dissipate energy at each location used in the structural model.
- Any material is allowed to be used in a damping device.

If a damping device is approved, the damping device shall not deviate from the proposed design approved through this process in the final structural model. If a team wishes to change their damping device in any way (e.g., installation location, connection to structure, material, etc.) after the results of the damper proposal, they must submit a revised damper proposal; however, they will lose any bonus given to them in this category. Moreover, the device may only be located at the approved locations. Furthermore, the damping device must not interfere with dead load installation locations.

Teams must submit only one damping device proposal by the final deadline. The SDC Chairs will determine if a device is approved within 14 days of the proposal being submitted. If the device is not approved and it is after the final deadline, teams are not allowed to use the disapproved device on their model.

All damping devices will be checked during pre-judging of structures. Damping devices that have not been approved by the SDC Chairs or deviate from the approved damping device proposal (e.g., installation location, connection to structure, material, etc.) will have to be removed and the team will lose the corresponding bonus. If a team is unable to remove an unapproved damping device, the structure will be considered collapsed for all ground motions.

A.2 Damping Proposal Requirements

2023 Damper Proposal Requirements and Rubric

Only teams that want to incorporate a damper in their structure are required to submit this damper proposal. The proposal will be evaluated by the SDC Chairs, and the result will be communicated to each team's team captain. **Remember, this proposal is not compulsory to participate in the 2023 Seismic Design Competition.**

This document describes items that must be included in the damper proposal and provides guidelines for teams to submit a high-quality proposal. Scoring of the damping proposals will be based on the requirements and rubric provided in this document. This document does not override the Official Rules; it is meant to supplement the official rules by providing formatting and content requirements of the design proposal.

1. **Formatting Requirements**
   - **The proposal shall not exceed 2 pages**, including the title page.
   - Any deviation from the formatting requirements will result in substantial deductions from the proposal score at the discretion of the SDC Chairs.

2. **Plagiarism Requirements**
   - Plagiarism is strictly prohibited and may result in disqualification or non-invitation to compete. Any citation style is accepted, as long as it is consistent. Works Cited or References pages are required but do not count toward the page limit. See Section 4.7 of the Official Rules for more information.

3. **Page Content Requirements**
   - Pages 1-2: Content
     - Name of the school, image(s) of the proposed damper device, and detailed description of the damper's materials, construction, mechanism, installation locations and reasoning behind the usage of this damper.
     - Proposals will be judged on the mentioned rubric below.
   - Page(s) 3(+): Works Cited
     - Teams must cite the references that they use in creating their proposal.
     - No additional content for the proposal may be included on the Works Cited page(s).

4. **Submission Requirements**

   A PDF of the document must be emailed to the SDC Chairs at the following email address by the date listed on the competition website. The SDC Chairs will confirm the submission within 48 hours of receiving it. If the team does not hear back from the SDC Chairs, please reach out to confirm the submission was received.

sdc@eeri.org

Page **1** of **2**

2023 Damper Proposal Requirements and Rubric

5. **Rubric**

This rubric is intended to serve as a guide to describe how teams can perform better in each category of the design proposal.

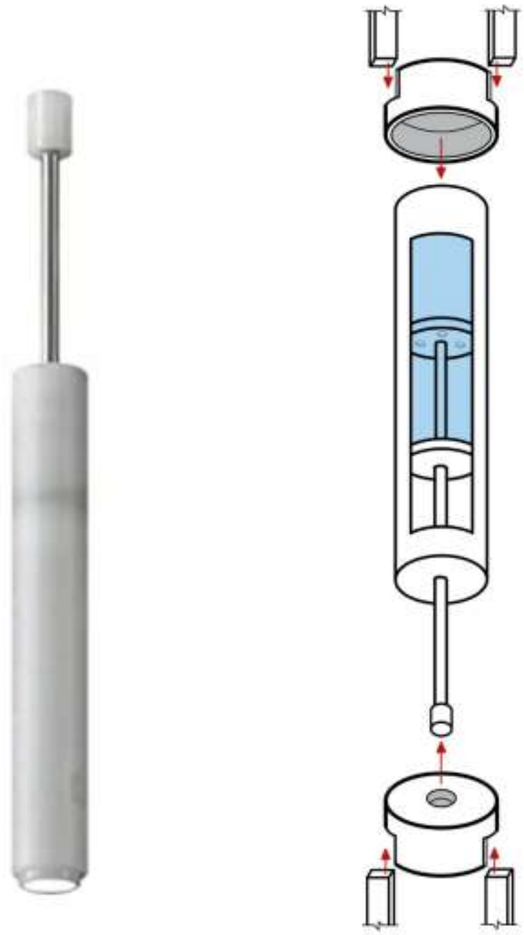
Category/Description	An excellent proposal…	A poor proposal…	Points
Device Description and Mechanism: Description of the damper's components, materials, and illustration of how the damper would dissipate the energy.	delivers a complete definition of the shape of the damper, including the materials used; has a clear interpretation of the mechanism of the damper.	demonstrates limited description of the damper; demonstrates limited understanding of the mechanism.	**3**
Structural Benefits and Research: Explaining the reason(s) behind incorporating a damper into your structure and the research done around it.	demonstrates the effect of the damper on the relative displacement of the structure; proposes relevant installation locations to maximize the use of the damper; shows a clear understanding of the energy dissipation in the structure and the effect of the damper's location.	provides minimalist information on the effect of the damper, its location and how energy dissipates throughout the entire structure.	**3**
Overall Structural Analysis: Structural analysis of the structure performance with the proposed damper.	describes expected relative displacement and acceleration of the structure with and without the damper; Cost analysis demonstrating the cost of implementing the damper in real building.	hasn't shown the impact of the damper on the overall structural performance; couldn't provide a prediction on the cost of using this damper in a building.	**3**

A.3 Damping Proposal

EERI SDC 2023 Damper Proposal — Fluid Damper Design

California Polytechnic State University, San luis Obispo Student Chapter

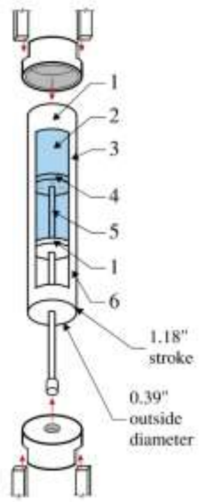
of the Earthquake Engineering Research Institute



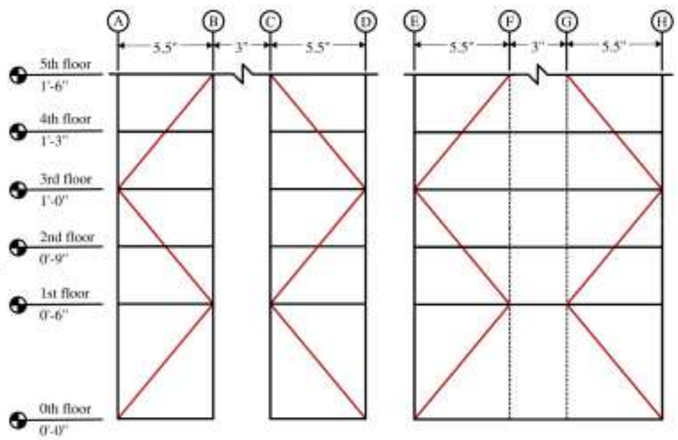
By Tynan Castro, Payton Filippin, Payton McGee, Dalton Muck

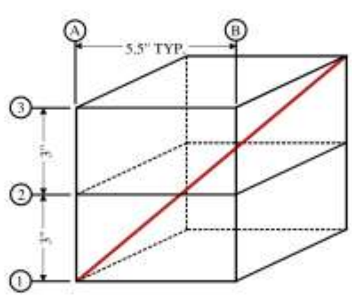
Date: December 16, 2022

This proposal describes the fluid viscous damping system for Cal Poly's Lucid Tower. It will be used to dissipate dynamic energy into heat and reduce building stiffness which will decrease the effects of acceleration and displacement on the structure [3]. The fluid viscous damper will consist of a piston inside a pressurized cylinder that will transfer fluid between chambers, when the structure experiences a lateral force, the piston will be compressed or extended to dampen the structure. Figure 1 illustrates this damping system, where the numbers correspond to: (1) end cover of the fluid chamber, (2) damping medium, (3) cylinder block, (4) piston which moves the medium during lateral movement, and (5) piston rod [6]. The team investigated various approaches to incorporate all the aspects and benefits of a viscous damper into the structural model and determined that shock absorbers from remote-controlled (RC) cars would be the best option for consistent performance.



The Bansbach Easylift FPD-1030A2-CW was selected, and it consists of a plastic cylinder block, a plastic piston, and oil as the medium. To connect the damper to the structure, a plastic cap or connection will be 3D printed. To analyze the impacts of the damper the following equation will be used: $F = CV^{\alpha}$, where F is the damper output force, C is the damping constant, V is the damper velocity, α is the velocity exponent (1.0 for Linear). The behavior of the fluid viscous damper is velocity dependent [2]. The velocity exponent can be modeled as linear [2]. A small-scale model will be built and subjected to a free vibration test along with the logarithmic decrement method being used to derive the dampers characteristics. The Maxwell model of viscoelasticity will also be used to demonstrate a stiffness spring in series with a pure dashpot, ultimately producing the elastic behavior of the damper [2]. The placement of the dampers will be at the location of highest velocity, which will be where there is the highest displacement, due to velocity being the derivative of displacement. The dampers, indicated in red, will be used from Levels 0-9, spanning every two floors except the first as represented in Figure 2. Spanning two floors allows for optimization of each damper's capacity as well as minimizing the overall building weight and cost. The dampers will span from interior column to outside corner column to limit interference with the structural system as seen in Figure 3. There are four dampers symmetric along both axes per level, which will reduce any unexpected torsional effects on the building.





A response spectra graph demonstrates the effects of implementing dampers within a structure. The building would have an inherent damping ratio of ~5% which with a damping system would increase to ~15% [1]. The corresponding decrease in acceleration will also result in a decrease in displacement. While there is an upfront cost of adding a damping system, there will be a decrease in both building construction and earthquake repair costs. With the added performance benefits of a damping system, other structural members can be sized down and reduce material use [5]. Lower expected displacements during seismic events will also "[prevent] catastrophic damage and costly repairs" [4]. Overall, incorporating dampers in the structure increases building resiliency, prevents building failure, and reduces costs.

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Appendix B. Investigation of Damping Approaches

B.1 Fluid Viscous Damper

Notes on Viscous Dampers as Used in Prior Snr. Projects

Research

Payton Filippin

Garrett Barker & Alex Poirier

Dynamic Response of Elastic Two Story Steel Moment Frames Scaled Structure Equipped with Viscous Dampers

"Dampers are commonly implemented in resilient structures that perform better in a design basis earthquake, reducing the seismic cost and downtime "

"The analytical model was capable of producing results consistent with experimental data. This suggests the modeling of dampers in structural design can be reliable and showcases the utility of the application of dampers in high seismic zones.

Introduction

They begin by stating the purpose is to minimize structural and non-structural building damage by reducing structural acceleration. They state that a building's damping ratio is conservatively chosen as 5% however, that changes due to material, building geometry, the system type and even the earthquake itself. They cite Wang & Lara IV 2019, a prior senior project, and use their results as assumptions in their project.

Methods

The attached viscous dampers to a two-story elastic steel moment frame structure. They then ran a Free Vibrations test and analyzed it with the Log-Dec Method. Then a Forced Vibration Test was run and analyzed with the half-power Bandwidth Method. An ETABS model was created to digitally analyze the structure with the data collected from the shaking tests. The ETABS model was constructed with assumptions and modeling choices outlined in Gerbo's 2014 Thesis. The Dampers were also modeling based upon the work done in Wang & Lara IV, 2019. The Damper was set to be a "Link" between two joints and given damping capabilities in the U1 direction (Axial)

Figure 1: Link Properties Menu in ETABS

The data was captured using a NI 9234 Data Connection Module which is nested within a NI Data Acquisition Figure. This process is very complicated and beyond our current ability as it leans heavily on frequency analysis. The purpose is to create a frequency response spectrum to approximate the fundamental frequency of the structure. As well as a power spectrum to note any additional mode shapes.

Big Takeaways

Recent studies by Wang & Lara IV (2019) and Gerbo (2014) have yielded reliable insights that warrant further investigation. Notably, the implementation of a single damper system on each side of a structure resulted in a significant reduction of both accelerations and forces, achieving an impressive 45% decrease. However, an interesting observation is the diminishing returns of additional dampers. As more dampers are introduced, the energy dissipation per damper in the system reduces, potentially due to the non-linear behavior exhibited. It is worth noting that the intricacies of collecting and analyzing raw data for this purpose are intricate and complex. This aspect could potentially be explored in greater depth through discussions with Anahid and Peter, where the balance between analytical depth and project scope can be evaluated.

Tiffany Wang & Roman Lara IV

Characteristics of a Viscous Damper: Finding the Damping Coefficient

"This experimentation data was used to find the damping coefficient of a viscous damper alongside damping characteristics."

" 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"

Introduction

They begin by saying that this is a topic that undergrads do not dive that deep into. They also immediately bring up the $F = CV^\alpha$ equation that we are also going to use. Also, there is a decent amount of guess and check when it relates to the ETABS modeling. They are only testing one damper. They also prob the question if the damper is truly a viscous damper or if its viscoelastic which can be determined by the Hysteretic Curves produced by the damper.

Methods

So they also purchased their damper, however, they connected one end of the damper to a steel angle and the other end to the large shake table. Then, they ran a forced vibration test with a known forcing function and recorded the responses into an excel file. They used a calibrated load cell (calibrated using LabView and a Force Curve) to accurately record the values coming from the Voltmeter and the compactDAQ instruments.

The data was filtered and put through a Butterworth filter. Damper was set up as such in ETABS

Big Takeaways

The dampers were decided to be viscous AND non-linear due to the hysteretic curves. When the hysteretic curve of a structure is circular, symmetric, and centered on the origin, then its safe to assume the system has linear behavior. This is helpful to understand and differentiate which dampers have linear behaviors and which have non-linear behaviors. A damping coefficient can be derived once the behavior is determined. For simplicity, the damping coefficient can be set to $\alpha = 1$ for linear behavior.

B.2 Rocking Shear Walls

SDC EERI Rocking Shear Wall Design Considerations and Concerns

Dalton Muck, Undergraduate Student

Dept. of Architectural Engineering, California Polytechnic State University

San Luis Obispo, CA

Abstract

Using a rocking wall for the Seismic Design Competition (SDC) for Earthquake Engineering Research Institution (EERI) could reduce the likelihood of plastic hinging or failure at the base of the lateral system due to racking forces.

Introduction

This paper was written to help guide future Cal Poly SDC EERI members on the benefits and drawbacks of rocking shear walls and considerations for whether they are a good fit for a structure. Rocking shear walls are a type of lateral force-resisting system that is allowed to rock, unlike traditional shear walls. This allows it to have high initial stiffness while reducing plastic hinging at the base of the wall.

Shear Wall Vs. Rocking Walls

A traditional shear wall is a lateral and gravitational force-resisting system used in structures. It resists lateral forces such as wind and seismic loads. They are typically very stiff systems that reduce the sway and damage in a building. Rocking shear walls are similar to shear walls except they are allowed to rotate or rock back and forth with strong lateral forces. The advantages to allowing the wall to rock is that it lowers the damage after a strong lateral shaking, also known as plastic hinging, as shown in Figure 1.

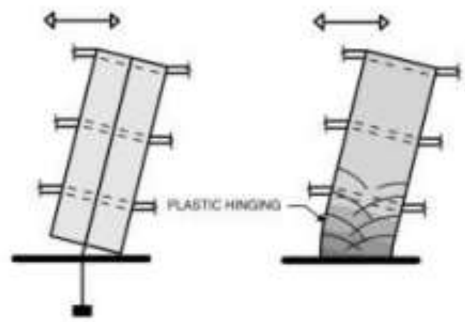


Figure 1: Rocking Wall on the Left and Traditional Wall on the Right

Balsa Wood Construction of Rocking Shear Walls

The materials for creating a rocking wall for SDC EERI differ from real-world construction, but the concepts are the same. Selecting wall placement is similar to placing any other lateral system; the wall should be aligned parallel to the lateral forces and distributed to reduce torsion in the structure. Traditionally the wall would go from the base to the roof, but it could also stop halfway, and another lateral system could continue to the top. The main portion of the wall is made from a sheet of balsa wood (it is recommended to use a medium to high density wood to resist the forces in the system). The wall is attached to the base using a wire that runs the full height of the wall. The wire needs to be secured to the wall. As seen in Figure 2, there are multiple ways to attach the wire.

The edges of the wall need to be able to lift off the base to allow for the rocking. Beams

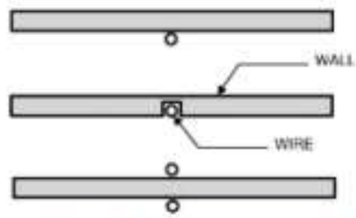


Figure 2: Options for Attaching Wire to Wall, Plan View

and diaphragm elements should be attached to the rocking wall to transfer the lateral forces to the wall.

Typical Failure Methods

There are two primary failure modes for rocking walls. The first common failure is a crushing at the corners as the wall tilts, as shown in Figure 4.

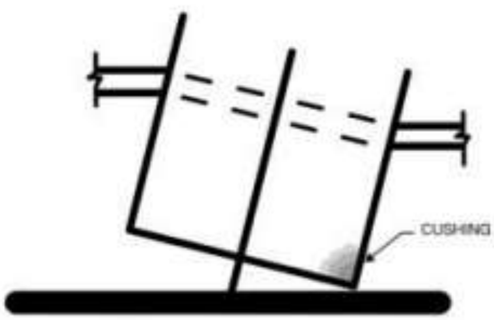


Figure 4: Crushing in Corner

The edge of the wall should be checked to see whether it can withstand this crushing force. The second failure mode to address is the flexure induced in the diaphragm due to the rocking of the wall, as. shown in Figure 5.

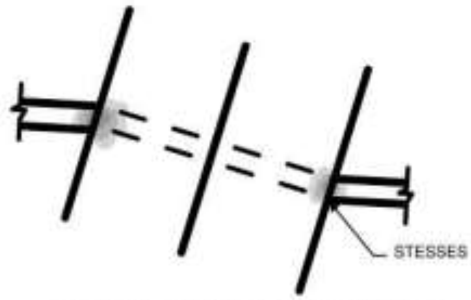
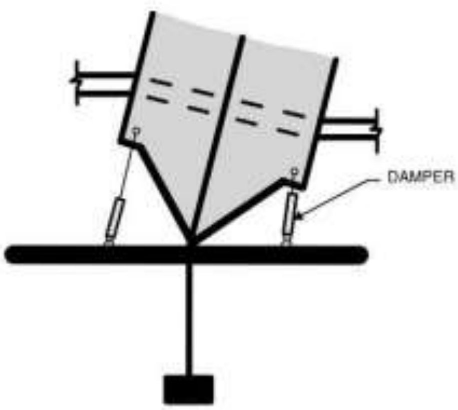


Figure 5: Stress Between Wall and Diaphragm

This failure should be addressed by making the connection strong enough to handle the forces, or by creating a connection that is able to transfer the vertical and horizontal forces without transferring the moment (a pinned connection). There are many different variations of rocking walls, and any design should be thoroughly thought through to distinguish possible failures.

Incorporation of Dampers into Rocking Shear Walls

Incorporating dampers into a rocking wall could effectively dissipate energy and reduce the forces flowing through the system. Typically, dampers are displacement-based and capture energy through friction or yielding, so they should be placed between points with high relative displacement. Different areas of displacement will lend themselves to different types of dampers. The most common damper used is a viscous damper placed in locations with high displacement to dissipate the greatest energy. A possible



design is shown in Figure 3.

Figure 3: Possible Damper Location

Another way to dissipate energy could be to place metal clips on either side of the wall that capture energy through yielding. If a dual rocking wall is used, this type of damper could be placed between the walls. As the walls move parallel to each other, the displacement can be captured in these dampers. These are just a few examples, and there are endless possibilities and designs for incorporating dampers into a rocking wall.

Modeling

There are several important steps to follow to model a rocking shear wall in ETABS or SAP2000. First, you will need to create a new model and define the structure's geometry, including the shear walls' location and size. You will also need to assign material properties to the wall, such as concrete and steel reinforcement, and a section property to the wall, defining its thickness and other geometric properties.

The next step is to specify the boundary conditions at the base of the wall to allow for rocking. This can be done using the "Joint Constraints" option in the "Define > Joints" menu. You will also need to assign a rocking hinge property to the base of the wall, which can be done using the "Frame Hinge Properties" option in the "Define > Frame Hinge Properties" menu.

There are several ways to model the wire or tendon in a rocking shear wall. One option is to use the tendon feature already built into ETABS and model it as a bonded or unbonded tendon. Alternatively, you can model the wire as an applied load.

It is important to note that the specific steps and options may vary depending on the version of ETABS or SAP2000 you are using and the specific details of your project. Overall, modeling rocking shear walls requires careful attention to detail and a thorough understanding of the unique design features that make these walls effective at resisting seismic forces.

Conclusions

Using a rocking wall for the Seismic Design Competition (SDC) for Earthquake Engineering Research Institution (EERI) could reduce the likelihood of plastic hinging or failure at the base due to racking forces. Additional experimental testing would provide insight on the feasibility of a rocking wall in your system.

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