Koç University
College of Engineering
Mech 491 Engineering Design Project Final Report

Spring 2023

Strengthening Structures against Earthquakes: Viscous Wall Dampers

Team Members:

	Name	Department	Student ID
1	Hakancan Öztürk	Mechanical Engineering	75723
2	Ömer Yavuz Yılmaz	Mechanical Engineering	76081
3	Onurcan Zer	Mechanical Engineering	72323
4			
5			

Project Advisors:

Name	Department
Metin Muradoğlu	Mechanical Engineering

Abstract

This study investigates the seismic resilience of buildings in earthquake-prone areas, particularly in Istanbul, using a newly developed Viscous Wall Dampers (VWD) system. The design and testing of the VWD system was performed using MATLAB and COMSOL 6.0 Multiphysics. Physical models of the VWD were created and then tested in an earthquake simulation based on the recent Kahramanmaraş earthquake. The system's performance was also evaluated using a scaled-down prototype, built in accordance with dimensional analysis. The analytical solution revealed that buildings can be conceptualized as mass-spring-damper systems, allowing for the optimization of structural resilience. The study also used finite element analysis to understand the behavior of the VWD system under different conditions and assess its damping capabilities. The results indicate that the VWD system effectively reduces structural damage caused by earthquakes by up to 60% in displacement. This research presents a potentially impactful approach to enhance the seismic resilience of buildings in earthquake-prone regions.

Table of contents

Section 1 Introduction

1.1 *Concept*

An earthquake is a natural phenomenon that arises from the sudden release of energy in the Earth's crust, leading to the generation of seismic waves. Such seismic waves have the potential to cause significant damage to buildings and infrastructure, thus presenting a threat to human safety and well-being. Turkey is located in a seismically active region where fault lines traverse, and the likelihood of an earthquake occurring in Istanbul is high. Unfortunately, many structures and buildings in Istanbul lack the necessary resilience to withstand earthquakes. As such, these buildings must either undergo demolition and reconstruction or retrofitting to enhance their seismic performance. One effective method for enhancing a building's seismic performance is through the use of earthquake isolator systems. Of the various isolator systems available, viscous wall dampers stand out as the most suitable option for the Istanbul earthquake scenario. Viscous wall dampers are devices installed in structures to mitigate the energy of seismic waves, thereby reducing damage to the building. These devices consist of a piston enclosed in a cylinder filled with a viscous fluid. During an earthquake, the piston moves through the fluid, which acts as a damping agent, effectively dissipating the energy of the seismic wave. In conclusion, given the imminent threat of an earthquake in Istanbul, it is imperative that measures be taken to enhance the seismic resilience of buildings and infrastructure. Viscous wall dampers present a viable solution to mitigate the destructive effects of seismic waves, making them an ideal choice for retrofitting buildings in Istanbul.

1.2 *Objectives*

This project is aimed at designing and optimising viscous wall dampers. Designing and optimising VWD is a complex process that requires careful consideration of a variety of factors. Shape and surface area of the interior plate in the viscous wall is the most important part of designing and performance of the isolator because the VWD absorbs the seismic energy by allowing the interior metal plates to slide against each other, with the viscous fluid providing resistance to this motion and this level of resistance is directly proportional to the surface area of the interior plates. The size of the dampers will depend on the size and weight of the building, as well as the expected level of seismic activity in the area. Another important factor is the type of fluid that is used in the dampers. The viscosity of the fluid can affect the damping properties of the system, and different types of fluids may be better suited to different types of buildings or structures. Overall, designing and optimising VWD requires a comprehensive understanding of the building's structural design, the expected seismic activity in the area. By carefully considering these factors, engineers can develop effective and efficient damping systems that can help protect buildings and infrastructure from earthquake damage. Main limitation of our project was the time. In this limited time, our group first made a gantt chart and we have progressed this project according to this gantt chart. Dimensional analysis is made to achieve best results for our prototype, and these dimensional analysis results are the crucial parameter which is used in the design of VWD. VWD consists of three main parts. Two of them are printed by a 3D printer, and the other part is viscous fluid which is obtained from an outside source. The challenge about 3D printing is that our school 3D printers are not good enough for printing VWD for building. This challenge is solved by modelling room instead of modelling building. After the prototyping stage is done, column displacement is measured via MATLAB. Comparison of experimental results are made by analytic results. Analytic solution is made by spring-mass-damper equations. The main challenge of analytic solution is to find proper variables to obtain analytic results. These variables are obtained by CFD analysis which is made with COMSOL.

1.3 *Elements of the engineering design involved*

This project involves a comprehensive approach to designing and testing a viscous wall damper seismic isolator. The design process begins with the creation of generic viscous wall design using Siemens NX. Finite element analyses will be performed using COMSOL Multiphysics to assess the performance of the design when implemented in a real building and a prototype. The simulations will be performed via coupling solid and fluid mechanics to represent the VWD system physics. The VWD system will be then optimised by altering the plate geometries and the medium fluid properties via COMSOL to obtain maximum performance. The optimised design will be produced at small-scale prototype, with dimensions adjusted accordingly. During the testing phase, the prototype will be subjected to seismic activity, and the performance of the isolator will be measured and analysed using a tracking system with slow motion camera via MATLAB. These comprehensive testing procedures will allow for a thorough evaluation of the effectiveness of the VWD, with real-world applications in mind.

1.4 *Background and literature review*

Viscous wall dampers (VWD) are a type of base isolation technology that incorporates damping elements in the form of viscous fluid-filled walls. According to Hejazi, the VWD consists of a series of vertical wall panels containing a viscous fluid, which is sealed between two metal plates[1]. The panels are connected to the building's structural frame and foundation, creating a protective barrier that absorbs and dissipates seismic energy. During an earthquake, the ground motion is transferred to the building's foundation. The VWD absorbs the seismic energy by allowing the metal plates to slide against each other, with the viscous fluid providing resistance to this motion. This resistance generates shear forces that dissipate the energy, reducing the overall acceleration and displacement experienced by the building. Consequently, the structural integrity of the building is maintained, and damage is minimised. While they are just one of many approaches used by engineers and architects to protect buildings from seismic activity, they have proven to be effective and reliable in reducing the risks associated with earthquakes.Figure 1 shows the general structure and design of VWD.

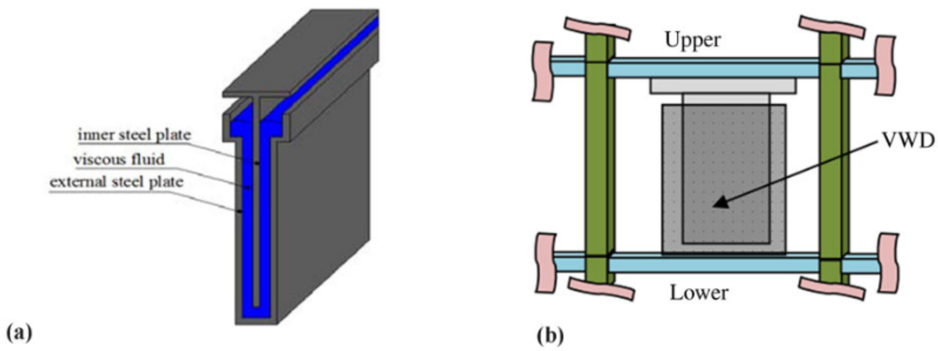

Figure 1 Schematic view of VWD (a) Parts of VWD. (b) VWD position in the frame bay [1].

1.5 *Approach*

In this project, a rigorous and systematic approach was taken to designing and optimising a Viscous Wall Damper (VWD) system. The initial stage involved a comprehensive literature review to gain a deep understanding of the working principles and overall structure of VWD systems, as well as to identify key design considerations and challenges. Based on this research, a VWD system was designed, taking into account factors such as the expected seismic activity in the area and the specific characteristics of the building. The design was then subjected to an optimization process using advanced computer simulations, such as finite element analysis. This involved modelling the behaviour of the VWD and the structure under earthquake loading, and evaluating the performance of different design configurations. Through this simulation process, engineers were able to identify the optimal VWD design that minimised structural damage and ensured the safety of the occupants. The final design was then produced at prototype levels and tested in experiments to assess its real-world performance. Overall, this project exemplifies a rigorous and data-driven approach to designing and optimising VWD systems, which is critical for ensuring the safety and resilience of buildings in earthquake-prone regions.

Section 2 Statement of work

2.1 *Methodology*

The design phase of the VWD was executed using Siemens NX. In the CAD environment, the VWD design was created, incorporating precise dimensions based on the physical models. Subsequently, the designs were seamlessly imported into COMSOL 6.0 Multiphysics, a leading finite element analysis (FEA) software, where sophisticated simulations of the components within the system were conducted using coupled physics to. This involved configuring the materials and fluids used in the system to accurately represent real-world conditions. The optimised design was then translated into analytical form and subjected to extensive testing in an earthquake simulation where the seismic data was acquired for the Kahramanmaraş earthquake. The testing aimed to validate the effectiveness of the VWD in mitigating vibrations and ensuring its durability under various simulated seismic conditions. To further evaluate the VWD's performance, a scaled-down version of the prototype and system was constructed and tracked using MATLAB. The experimental data obtained from physical testing, analytical calculations, and finite element analysis were meticulously compared and analysed using MATLAB's powerful computational capabilities. This comprehensive analysis allowed for a comprehensive understanding of the VWD's behaviour and its ability to effectively dampen vibrations.

2.2 *Modelling*

2.2.1 Analytic Solution

Extensive research was conducted to gain a comprehensive understanding of the dynamic response of structures in the face of seismic events, with a specific focus on elucidating the transmission of base-induced movements to the upper floors. As our investigations progressed, it became evident that these structures could be conceptualised as mass-spring-damper systems which are shown in Figure 1 with 2D and Figure 2 with 3D. The spring-like behaviour originates primarily from the columns, drawing upon the principles of cantilever beams and the consequential bending moments they generate. The stiffness calculation of the springs originating from the columns is shown in Formula 1. The damper system originates from both the structure of the building and the VWDs we added in our project. Through a comprehensive exploration, we not only acknowledged the fundamental characteristics of these systems, encompassing the intricate interdependence among mass, spring elements, and damping mechanisms but also diligently considered force equilibrium in the vertical direction. By meticulously accounting for these factors, we successfully derived a generalised equation, represented by Formula 2, which encapsulates the dynamics of the system under seismic conditions. This pivotal equation serves as a cornerstone for further advancing our comprehension of the system's seismic response, enabling us to refine our design methodologies and conduct rigorous analyses aimed at optimising the structural resilience of these architectural constructs.

$$k_{column} = 3 \cdot \frac{E \cdot I_{Column}}{h^3} \quad (1)$$

Formula 1 [6]

$$k_{VWD} << k_{column}$$

$$m \cdot u'' + c_{building} \cdot u' + 2 \cdot c_{VWD} \cdot u' + 4 \cdot k_{column} \cdot u + 2\, k_{VWD} \cdot u = - m \cdot u''_{ground} \quad (2)$$

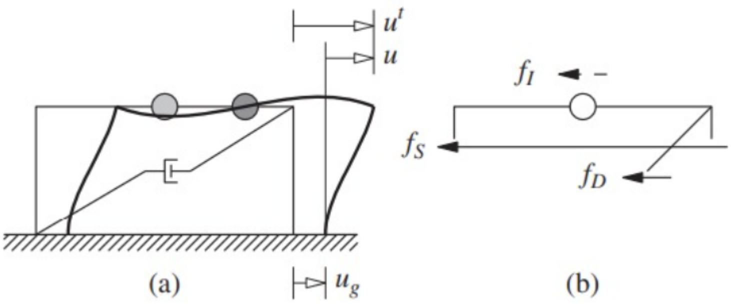

Figure 2 2D Schematic view of a- the structure, b- the displacement convention **[2]**

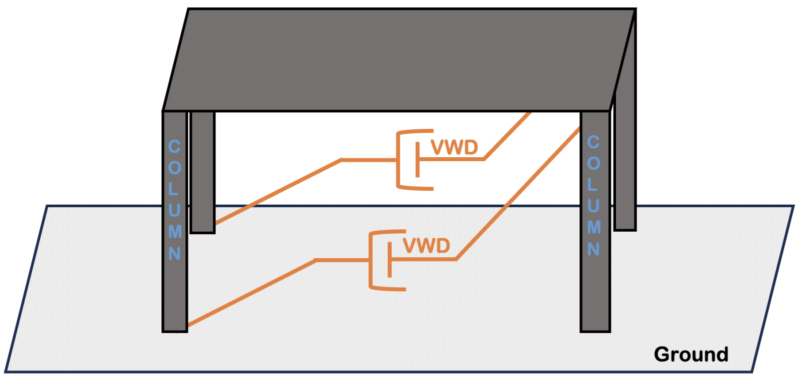

Figure 3 3D Schematic view of the structure with 2 VWDs

Upon the successful derivation of these fundamental equations, our endeavours extended to the determination of a transfer function that establishes the relationship between ground displacement and the corresponding displacement of the upper floors. This transfer function, obtained by applying the Laplace transform to the system equations, assumes paramount importance as it enables us to employ sophisticated numerical tools such as MATLAB for further analysis and simulations. Formula 3 represents the resulting transfer function.

$$\frac{U(s)}{U_{ground}(s)} = \frac{(-m \cdot s^2)}{(m \cdot s^2 + c_{total} \cdot s + k_{total})} \tag{3}$$

By utilising MATLAB, the transfer function of fluid systems was defined to compare the responses of fluids with different viscosities in the upper floor during the Kahramanmaraş earthquake[3]. The transfer function analysis allowed for the generation of graphical representations, enabling a comprehensive comparison of the fluid system behaviours.

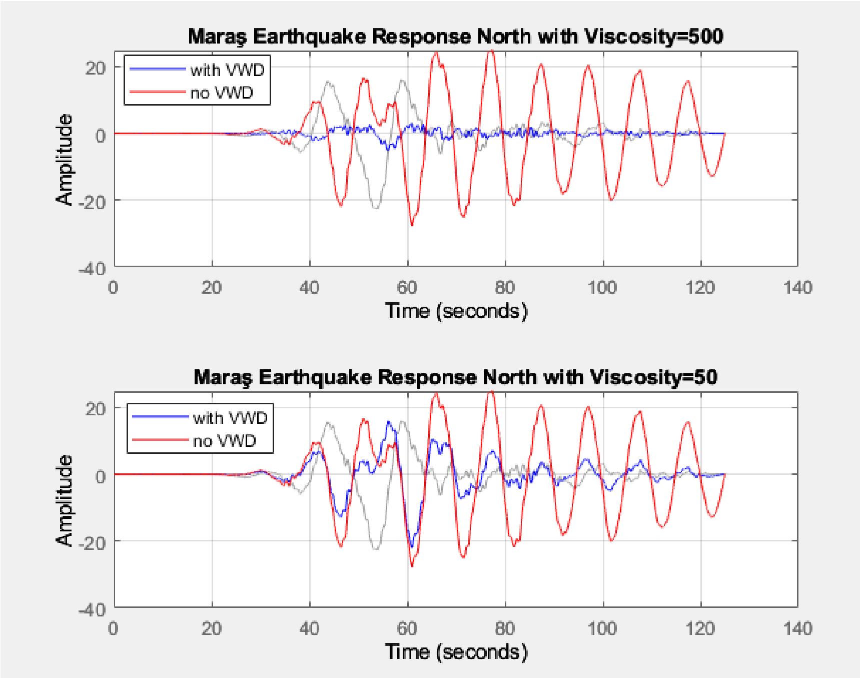

Figure 4 Kahramanmaraş Earthquake Response of Structure with VWD top- μ= 50 Pa*s, bottom- μ= 1000 Pa*s

2.2.2 Pi Numbers

Upon analysis regarding the dimensions of the building designated as our prototype and a comprehensive analysis of the material properties employed in its construction, we embarked upon an intricate process of determining the remaining building and prototype properties through a meticulous exploration of the Pi numbers. By aligning these esteemed mathematical constants with their tangible counterparts in the physical world, we adeptly derived the precise properties and values of the structures within the system[4]. Through this rigorous methodology, we ensured a harmonious congruence between theoretical calculations and practical reality, thus elevating the overall integrity and accuracy of our findings. During the meticulous computation of these crucial Pi numbers, our initial focus was directed towards identifying the key factors that influence the displacement of the upper ground within the system. These factors encompassed the displacement (u) resulting from seismic activities, the height of the column (h) , the modulus of elasticity (E) characterising the structural integrity of the building, the area inertia (I_c) of columns situated within the building, the overall mass (m) of the structure, the gap (y_{gap}) between the inner plate and outer plate in the VWD, the area of the inner plate (A) within the VWD, as well as the density (d) and viscosity (μ) of the fluid contained within the VWD. By meticulously examining the aforementioned variables, we systematically generated Pi numbers by incorporating key parameters such as the building's height, the viscosity of the fluid employed, and the mass of the structure. By conscientiously considering these multifaceted variables, we endeavoured to ensure a comprehensive understanding of the underlying dynamics governing the system and subsequently employed the determined Pi numbers to achieve a precise alignment with real-world observations and phenomena. In Table 1, the seven Pi numbers and the values of these pi numbers for real-life and the prototype system in the project are shown.

Table 1.

	Pi Formula	Real-Life Pi Values	Prototype Pi Values
π_1	$\frac{u}{h}$	$\frac{0.15}{3} = 0.05$	$\frac{0.01}{0.1568} = 0.0638$

π_2	$\frac{I_c}{h^4}$	$\frac{6.75 \cdot 10^{-4}}{3^4} = 8.33 \cdot 10^{-6}$	$\frac{5.19 \cdot 10^{-9}}{0.1568^4} = 8.59 \cdot 10^{-6}$
π_3	$\frac{E \cdot m}{\mu^2 \cdot h}$	$\frac{38 \cdot 10^9 \cdot 30000}{50^2 \cdot 3} = 156 \cdot 10^6$	$\frac{1.9 \cdot 10^9 \cdot 5}{0.615^2 \cdot 0.1568} = 160 \cdot 10^6$
π_4	$\frac{u_{ground}}{h}$	$\frac{0.15}{3} = 0.05$	$\frac{0.01}{0.1568} = 0.0638$
π_5	$\frac{A_{plate}}{h^2}$	$\frac{3.078}{3^2} = 0.342$	$\frac{0.00863}{0.1568^2} = 0.351$
π_6	$\frac{y_{gap}}{h}$	$\frac{0.075}{3} = 0.025$	$\frac{0.003}{0.1568} = 0.020$
π_7	$\frac{d \cdot h^3}{m}$	$\frac{945 \cdot 3^3}{30000} = 0.85$	$\frac{1250 \cdot 0.1568^3}{5} = 0.968$

2.3 *Finite element analysis*

The characterization of the VWDs depended on the CFD analyses performed on the COMSOL 6.0 Multiphysics software. The simplified twin of the generic VWD was modelled and analysed in the simulation domain using multiphysics finite element method. The geometrical properties of the VWD was obtained from the manufacturer's products and were adjusted according to the Koç University structural properties in terms of wall thickness and height. The analyses were performed for several purposes and encompass various scenarios aimed to a- validate, b- characterise, c- optimise, d- explore novel designs. For these purposes over 10 different CFD models were simulated on the engineering workstation Akasya.

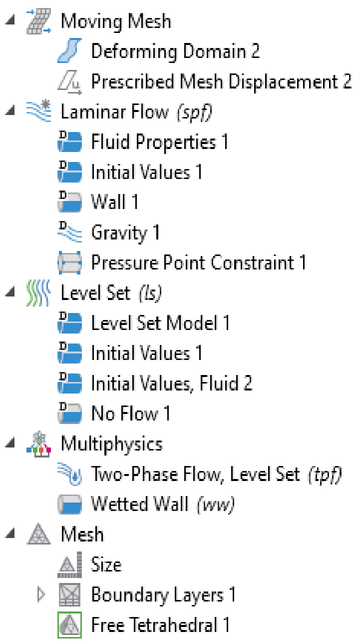

Figure 5 The workflow of the generic COMSOL simulations coupling the CFD and Level Set modules

The FEM analysis consists of several parts and varies from a conventional CFD simulation. The free surface of the viscous fluid was to be solved to better understand the fluidic interactions, therefore a level set module was used to solve the fluid-fluid interactions between the viscous fluid and the ambient air. This module was coupled with the laminar/creeping flow module to account for the individual fluid motions. The internal plate was defined with a prescribed motion that was later changed to see the effect of internal plate velocity to the damping as well. The simulations revealed that the effect of velocity to the damping force was linear.

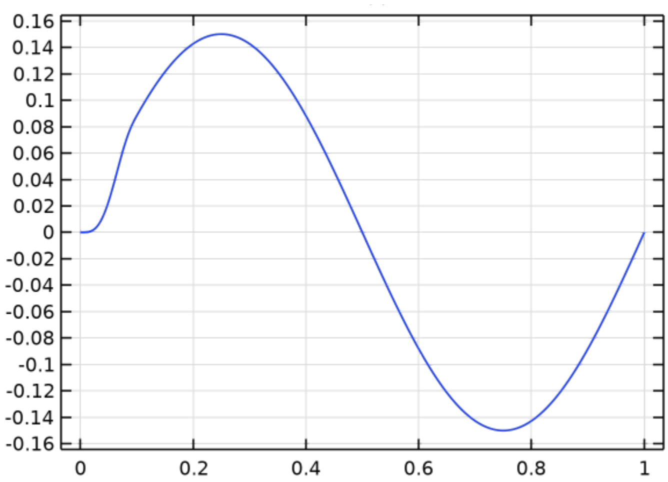

Figure 6 The generic inner wall displacement movement prescription where $f_{rotation}$= 1 Hz, the y-axis corresponds to the displacement in cm and the x-axis is time in secons

The CFD module also encompassed the gravitational effect and the boundaries with no flow such as the internal and external plates. The surface tension effects were neglected since their effect doesn't account for a big difference in the damping, also the characterization was done for 4 main viscosity values, namely, μ= {50, 100, 250, 1000} Pa*s. The relationship between the viscosity and the damping was found to be linear and this range encompasses the majority of the silicon oil products in the market [5]. Since the Re number for all the cases were far below 1, max 0.3, the flow regime can be classified as Stoke's/Creeping flow and the simulations were solved accordingly to reduce the computational load of inertial terms in the Navier Stokes equation.

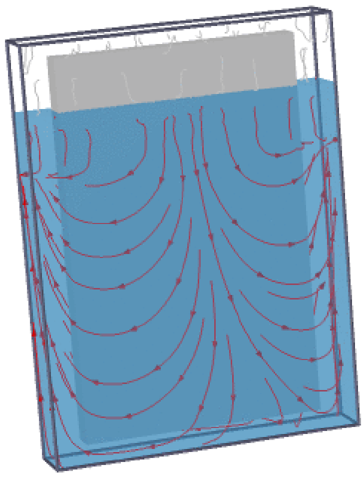

Figure 7 The solution of the plain inner plate simulation, with the level set and streamlines red- silicon oil, gray- air

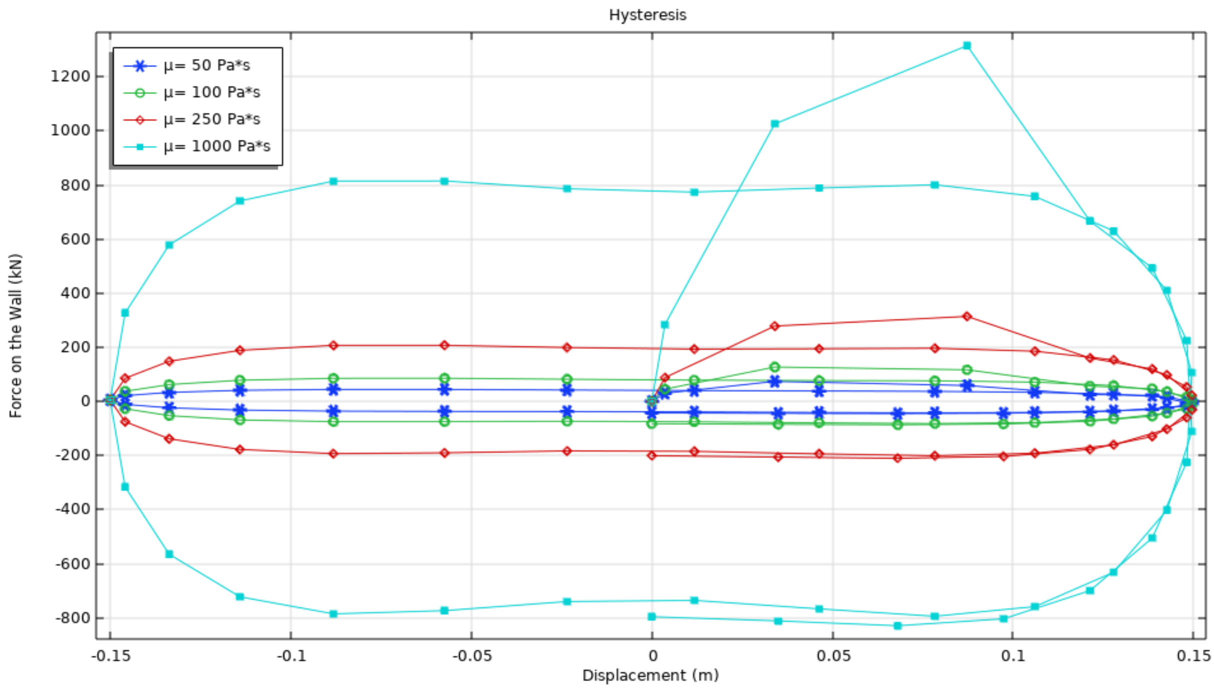

Figure 8. The hysteresis plot of the plain inner plate geometry with various viscosity values, where the area between the force-displacement curve corresponds to the dissipated/damped energy

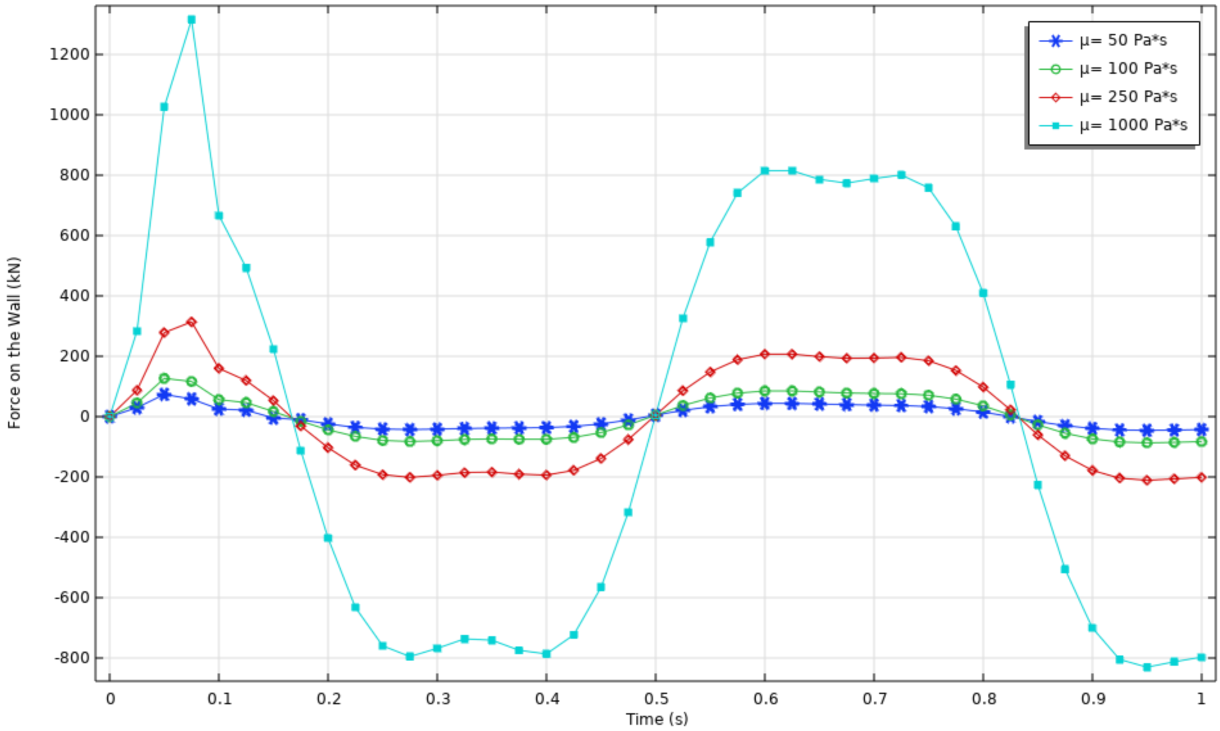

Figure 9 The force vs time graph, strictly following the displacement vs time graph due to the stokes regime and lack of inertial effects

The hysteresis plots were analysed on MATLAB and the areas were found, later to be used in the analytical solution. Since the damping of the VWD system cannot be expressed analytically these steps were necessary for an accurate analysis of the system. The analytical solutions were tested under the Kahramanmaraş earthquake data and the results are in the following sections. The damping coefficients were also interpolated for the prototype and were tested experimentally and analytically where the results are compared.

After solving for the plain rectangular inner plate, new designs were tested where the boundaries of the inner plate geometry was kept a constant slits were introduced to mimic the comb shape in two directions. With this study, we investigated if the inner plate geometry had an effect on the overall damping.

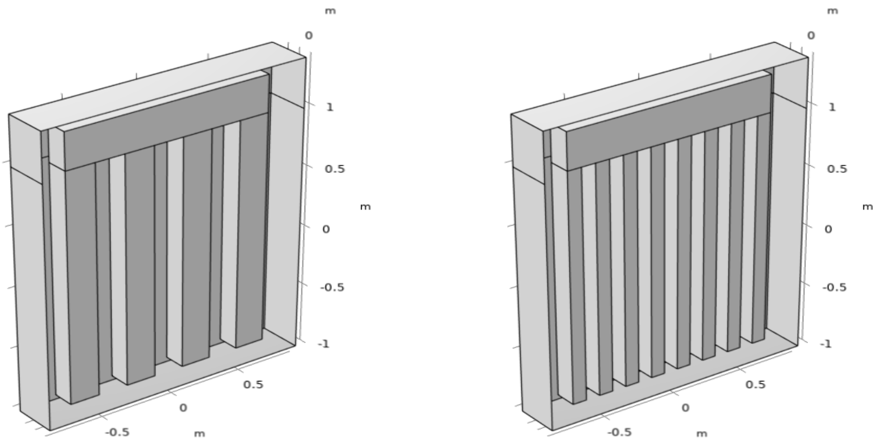

Figure 10 The inner plate design with horizontal slits where the comb numbers for left- nC= 4, right- nC= 8

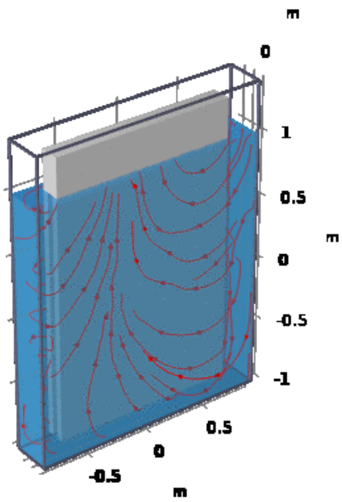

Figure 11 The solution of the inner plate with a longitudinal slit simulation, with the level set and streamlines red- silicon oil, gray- air

Our investigation of a more identical geometry by introducing slits yielded with nearly identical results in terms of force and energy. However, with less building material and mass we can produce inner plates to perform the same. Therefore our efforts were not meaningless in terms of reducing the cost. The results for the comb geometries can be found in the appendix.

2.4 *Prototype fabrication and testing*

For the prototyping stage, lego bricks, and 3D printed parts are used to generate room for the building. One of the cornerstones of this project was the creation of a tangible, physical model. This allowed us to visualise the implementation of Viscous Wall Dampers (VWDs) and study their performance under simulated earthquake conditions. The goal was not only to create a representation of a real-world structure but also to ensure that the scale model authentically demonstrated the principles and effects of VWDs. The figure below shows the designed VWD's section view.

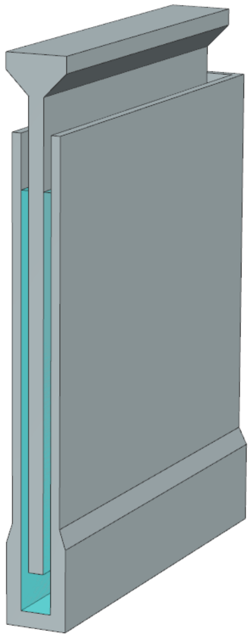

Figure 12 CAD design of VWD

The decision was made to model a room within a structure, as opposed to an entire building, mainly due to the limitations of the 3D printers available to us. The printers at our disposal were not capable of producing components at a scale appropriate for a full building model. Additionally, focusing on a single room allowed us to concentrate our efforts and resources, ensuring a detailed and accurate representation of how VWDs could be installed and operated within a structure. The figure below indicates the room model with installed VWD.

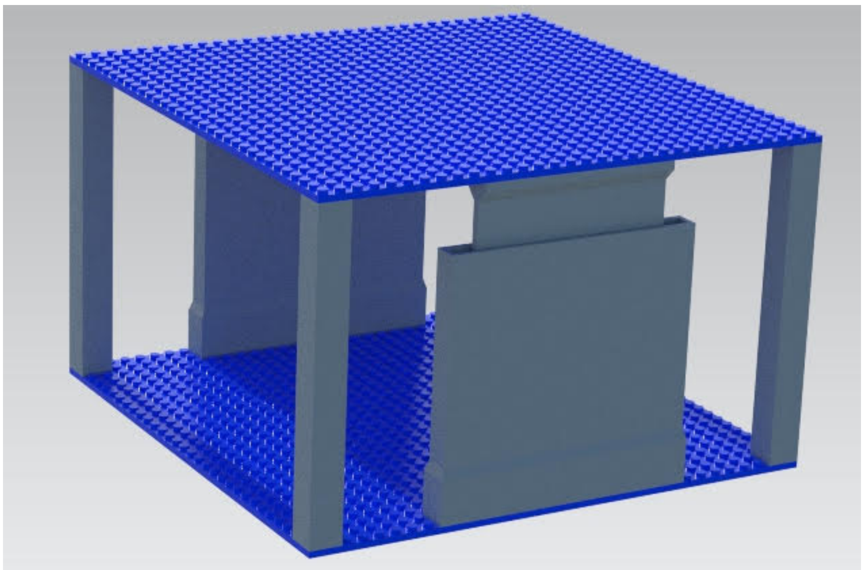

Figure 13 Render of final prototype system

LEGO bricks were selected as the primary construction material for the room. Their modular nature offered two key advantages. Firstly, it enabled us to easily assemble, modify, and disassemble our model during various stages of testing and analysis. Secondly, the physical properties of LEGO bricks, specifically their modulus of elasticity which is 1.9 GPa [7], closely match that of concrete when scaled appropriately.

This congruence in material properties allowed us to better simulate the real-world conditions of a concrete room in our scaled-down model.

The actual VWDs in our model were created using 3D printing techniques, filled with glycerin, a viscous fluid. Glycerin was chosen as it allowed us to control the viscosity with the addition of water, providing flexibility in our experiments. The use of a viscous fluid in the VWD was essential to accurately represent the damping mechanism that is the key to the VWDs function.

The simulation of earthquake conditions presented another challenge. We decided to construct a shaking table to mimic ground motion during an earthquake. A hardboard platform was mounted on rails to allow back-and-forth movement, and a DC motor was used to drive this motion. This setup offered a simplified but effective representation of the forces a building might experience during an earthquake. The figure below indicates the basic crankshaft mechanism that is used to mimic earthquakes.

Figure 14 Final motor coupling design of prototype consisting of a crankshaft mechanism

The goal was not only to construct a working model but also to ensure that it yielded quantifiable and analyzable data. Thus, specific LEGO bricks in the model were replaced with white versions to enable easy tracking of movement during testing. Using a high-speed camera and software like MATLAB, we were able to capture and analyse the displacement of these bricks, providing valuable data on the effects of the simulated earthquake and the performance of the VWDs. The figure below shows the final version of our prototype.

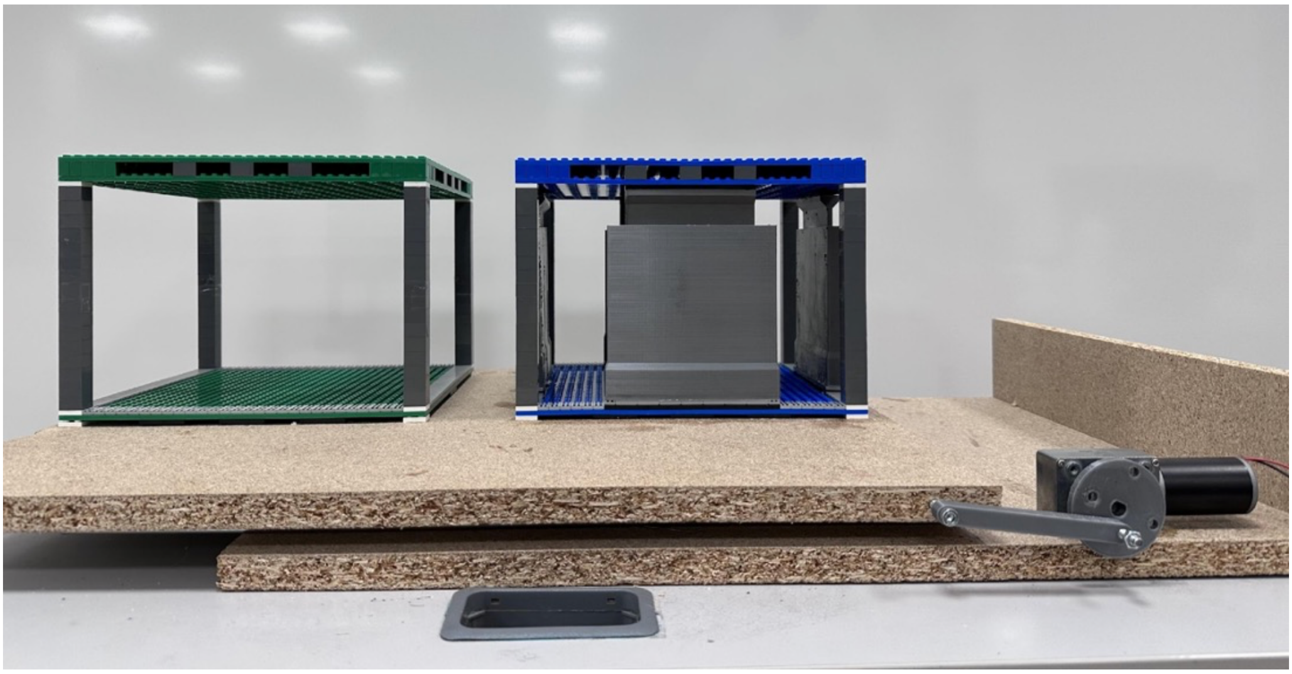

Figure 15 Final prototype design consisting of two structures and a motor system

The prototyping and experimental stages of this project were as enlightening as they were challenging. They brought to life the principles and theories studied, providing a practical, hands-on perspective on the subject. The success of these stages reaffirmed the viability of VWDs and emphasised the potential this technology holds for improving the seismic resilience of structures.

2.5 *Results and Comparison*

In order to analyse the effect of mass increase on the system in Prototype, the upper ground displacement values via MATLAB by applying the same earthquake effect to structures of different masses are shown in the figure below.

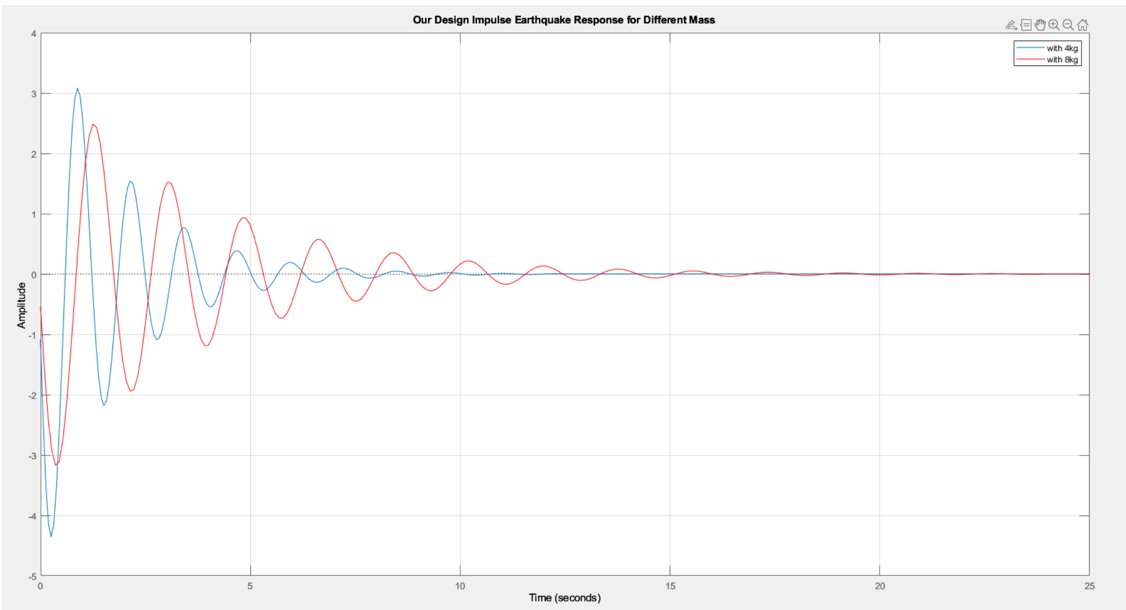

Figure 16 MATLAB Results for, blue- m= 4 kg, red- m= 8 kg

In order to understand the validation of the system, the earthquake effect, which we obtained by tracking, was put into the analytical solution transfer function and compared with the upper floor displacement obtained by tracking. The damping coefficient value of VWD in the analytical transfer function here is taken from COMSOL. These graphics are shown in the figure below in two separate buildings as the building with VWD and the building without VWD. The results obtained are very close to one and have low errors. This shows that the system is experimentally and analytically valid. To assess the validity of the system, a comprehensive analysis was conducted by incorporating the earthquake effect obtained through tracking into the analytical solution transfer function. The resulting upper floor displacement was then compared to the tracking data. The damping coefficient utilised in the analytical transfer function was derived from COMSOL, ensuring accuracy and consistency. The graphical representation of the comparison is depicted in the figure below, showcasing two separate scenarios: one with the inclusion of the VWD in a building, and another without the VWD. The obtained results indicate a high degree of agreement, with minimal errors observed between the analytical and experimental data. This convergence strongly indicates the experimental and analytical validation of the system.

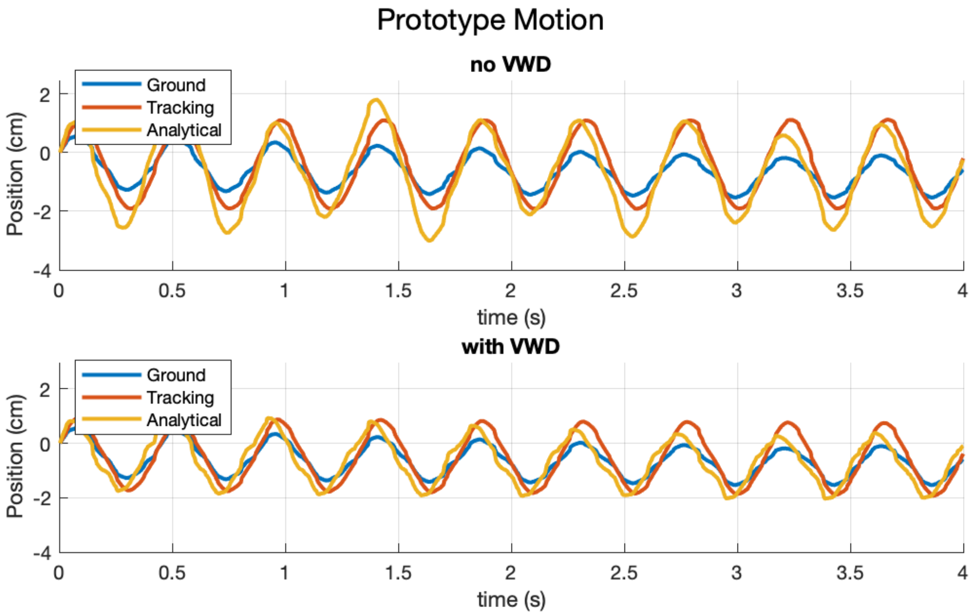

Figure 17 Comparison of the analytical result with experimental result

The remarkable consistency between the tracked and analytical solutions reaffirms the effectiveness of the VWD system in earthquake damage. This validation provides confidence in the system's performance and its ability to significantly reduce structural damage in real-life applications. The reduction in the analytical system was around 61% in terms of displacement of the damped system compared to the undamped. However, the experimental setup yields with 47% for a slow motion video run where the motion was provided steadily with a motor.

Section 3 Economic analysis

The production of the VWD was facilitated through the utilisation of a 3D printer, offering a cost-effective manufacturing solution. One of the primary expenses incurred in this project was associated with the construction of a scaled structure, along with the installation of a motorised system capable of simulating earthquake effects. The scaled structure was made from Lego which was bought in a Lego store due to both the practicality of its construction and the fact that its properties fit pi numbers. The earthquake effect is provided by the regular movement of the motor with the drawer rails of the chipboard. Furthermore, the cost of the viscous fluid used for manufacturing the inner and outer plates of the VWD was relatively affordable. A breakdown of the project costs can be found in Table 2 provided below. In addition to its cost-effectiveness, the VWD system holds significant market potential within society. The primary product's inexpensive production and ease of implementation in real-life buildings make it highly appealing for various applications. The VWD offers a practical and viable solution for effectively mitigating vibrations in buildings, ensuring enhanced structural stability and safety. Its affordability and user-friendly design contribute to its marketability and widespread adoption.

Table 2

Item	Cost(TL)
Lego Bricks	1500
Hardboard	1000
Rail	800
DC motor	800
Power Supply	300
Glyserin	300
Silicon Oil	200
PLA filament	300
Total	**5200**

Section 4 Summary and conclusions

Our study into the use of Viscous Wall Dampers (VWDs) for reinforcing structures against seismic activities signifies a key advancement in understanding and applying this potentially revolutionary technology. Our research, encompassing theoretical exploration, scale model construction, and data analysis, provides valuable insights into the practical effectiveness of VWDs. The findings affirm VWDs' ability to mitigate seismic vibrations, critical in regions like Istanbul, prone to earthquakes, and featuring dense urban infrastructure. Given the challenge of retrofitting buildings with traditional seismic isolation systems, VWDs present a flexible, effective solution with the unique advantage of being installable at any floor level.

The prototyping phase underlined the potential of creating scalable designs using basic materials and fabrication methods, demonstrating the accessibility of this technology. However, it also highlighted the need for improvement, notably a more powerful motor for the earthquake simulation table. The implications of our findings extend beyond just reducing physical damage from earthquakes. By mitigating seismic impacts on buildings, VWDs could reduce the social and economic costs of such disasters.

Our growing understanding of VWDs opens the door to further innovation and application of this technology. Future work involves refining the VWDs' design, exploring their implementation in diverse contexts, and investigating different materials and configurations. In conclusion, our exploration into VWDs as a tool for enhancing structural resilience against earthquakes has been promising. Our team remains committed to furthering this technology, aiming to create safer, more resilient environments for global communities.

Section 5 Future work and recommendations

Looking ahead, we plan to further explore the implementation and efficiency of VWDs in reducing seismic activity's impact on buildings. We hope to expand our research to cover more ground, including the application of VWDs in larger-scale models and the use of varying viscous fluid materials. We also would like to introduce the other transverse direction in our research by installing another motor perpendicular to the current one to simulate the earthquake more accurately.

We believe that continuous research and improvements in VWD technology will revolutionise the field of structural engineering, particularly in seismic-prone regions. We aim to be part of this revolution, contributing to creating safer, more resilient infrastructures that can withstand the test of nature. With the improved structural toughness, we can be significantly more prepared for the upcoming seismic challenges

Acknowledgments

Our research into Viscous Wall Dampers (VWDs) would not have been possible without the contribution and support of various individuals and resources. We would like to thank our university for providing the necessary facilities, equipment, and academic support throughout the research process. The experimental portion of our research required the use of advanced 3D printing technology, software tools, and engineering equipment, which our university graciously provided. We would like to extend our gratitude to Levent Demirkazık.

References

[1] Hejazi, F., Shoaei, M. D., Tousi, A., & Jaafar, M. S. (2016). Analytical model for viscous wall dampers. *Computer‐Aided Civil and Infrastructure Engineering*, *31*(5), 381-399.

[2] Humar, Jagmohan(2012). *Dynamics of structures*. CRC press,. p. 20-30

[3] ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA, “ESM Database,” ESM, https://esm-db.eu/ (accessed Jun. 13, 2023).

[4] Hidayaty E., Setio H. D., Surahman A., Moestopo M. Numerical analysis of viscous wall dampers on steel frame. 3rd International Conference on Sustainable Infrastructure and Built Environment, 2017.

[5] Shin-Etsu Silicone, https://www.shinetsusilicone-global.com/catalog/ (accessed Jun. 13, 2023).

[6] The Engineering ToolBox (2013). Cantilever Beams - Moments and Deflections. [online] Available at: https://www.engineeringtoolbox.com/cantilever-beams-d_1848.html [Accessed Day Month Year]

[7] Lee, S., Ha, J., Jo, S., Choi, J., Song, T., Il Park, W., ... & Paik, U. (2013). LEGO-like assembly of peelable, deformable components for integrated devices. Npg Asia Materials, 5(10), e66-e66.

Appendix

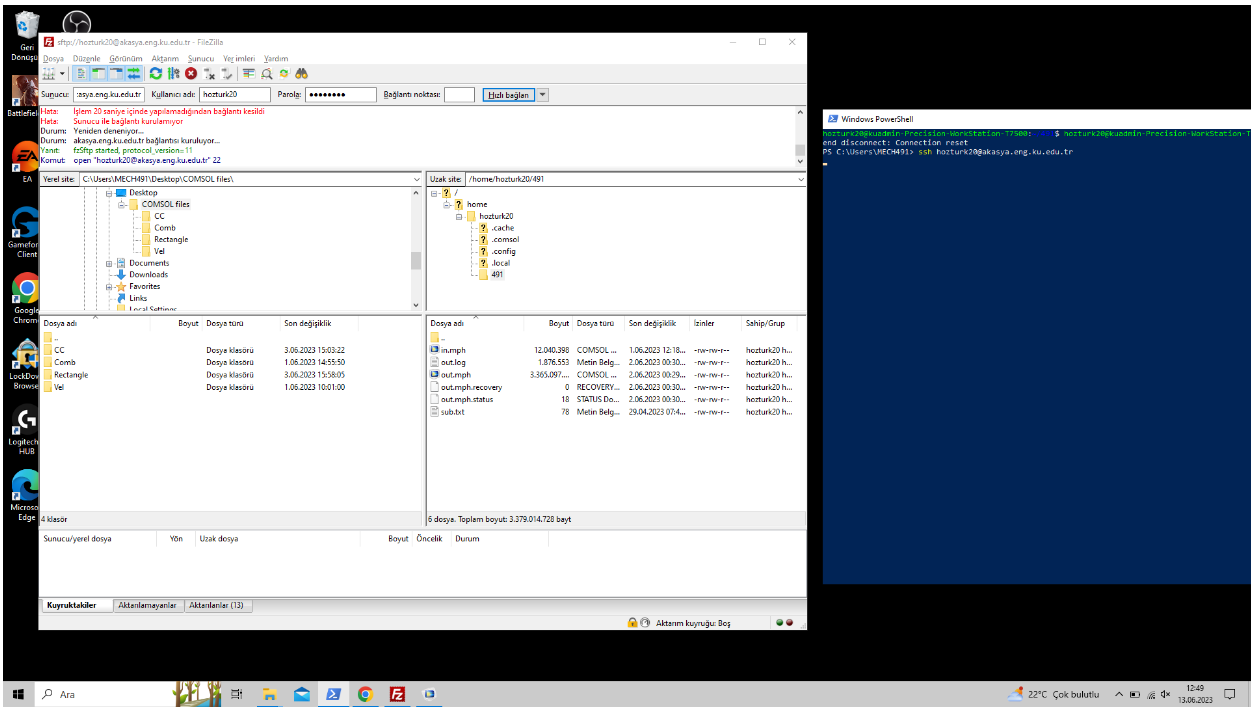

Figure 18 The interface used to run simulation on the Akasya Workstation left- Filezilla program that facilitates the file transfer, right- Windows PowerShell terminal that connects to the workstation via ssh protocol and receives commands from the user

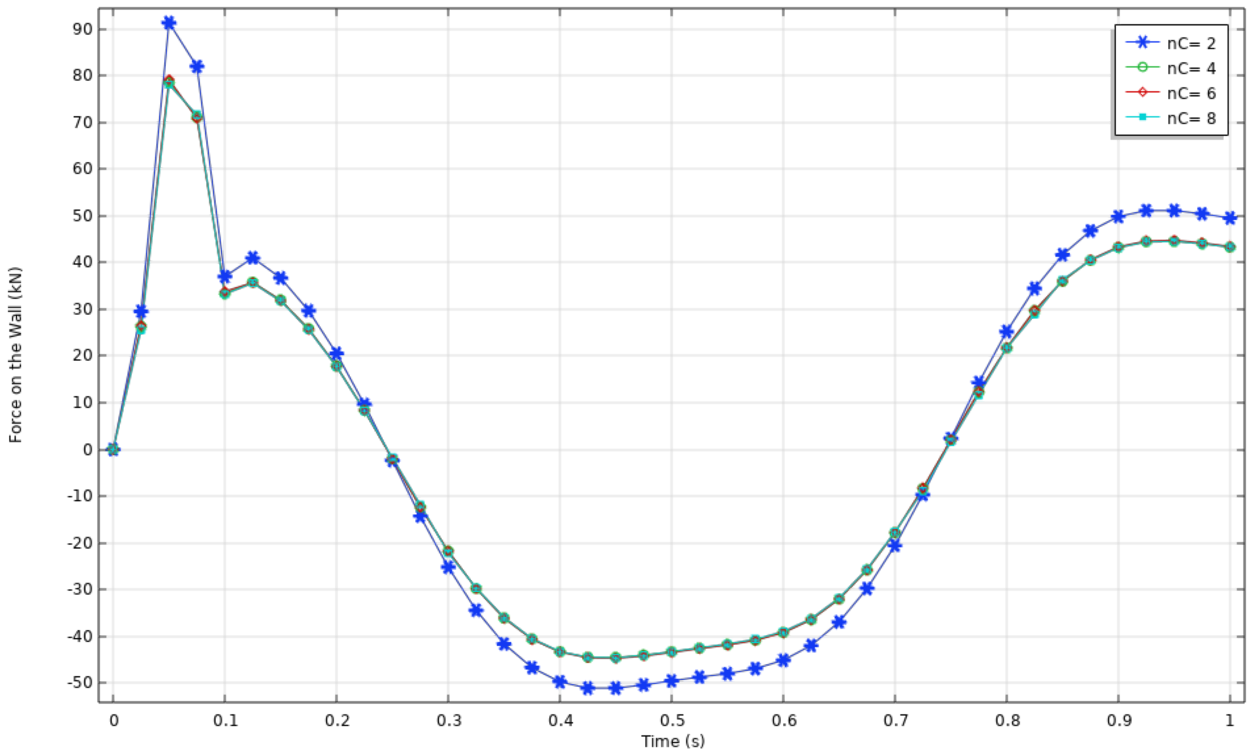

Figure 19 The horizontal slitting results results for different number of combs where μ= 100 Pa*s

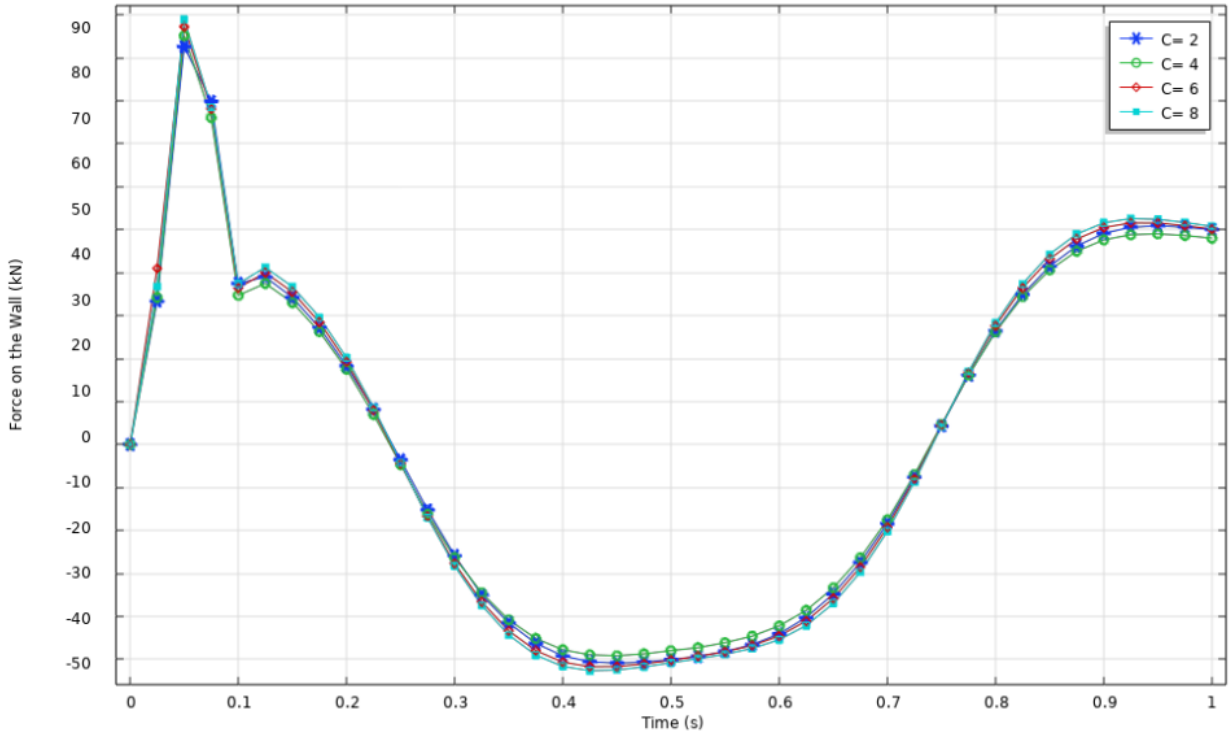

Figure 20 The longitudinal slitting results for different number of combs where μ= 100 Pa*s

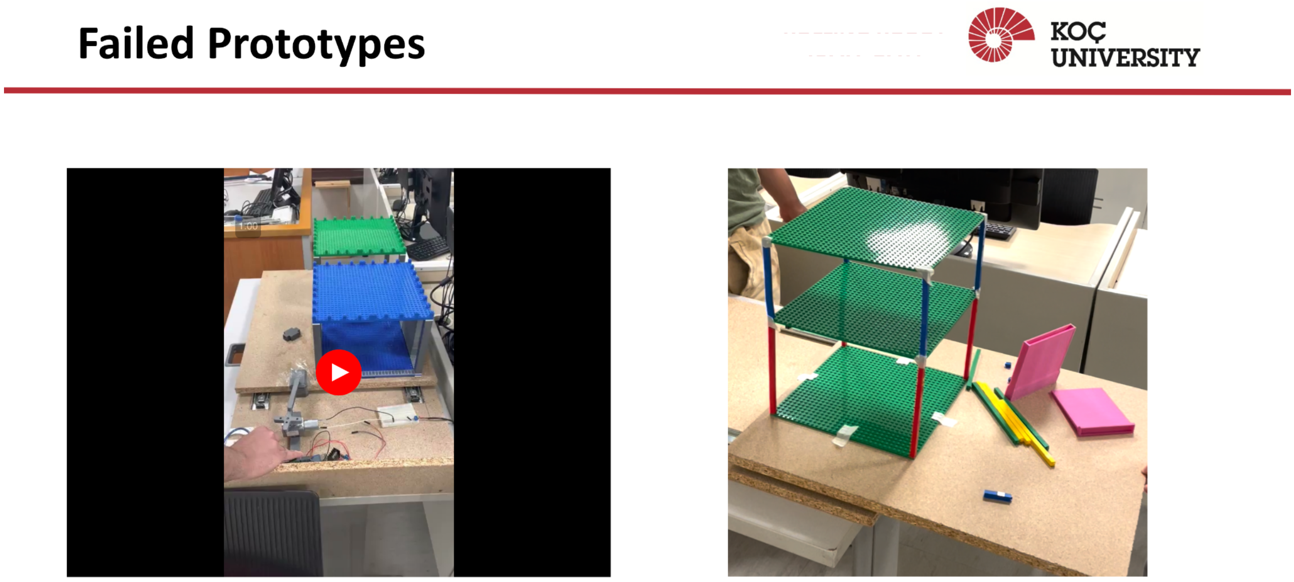

Figure 21 Some failed designs left- wrong motor connection to the ground, right- without utilisation of the pi groups

Tracking Code - MATLAB

```
close all, clear, clc
% Import the video
videoFile = 'motor1.mov'; % replace with your video file
videoReader = VideoReader(videoFile);
% Read the first frame and select points to track
frame = readFrame(videoReader);
imshow(frame);
title('Select points to track');
[xPoints, yPoints] = getpts;
close;
points = [xPoints, yPoints];
points_to_track = cornerPoints(points); % convert to cornerPoints object
% Create a point tracker
pointTracker = vision.PointTracker('MaxBidirectionalError', 2);
% Initialize the tracker with the initial point locations and the initial video
frame
initialize(pointTracker, points_to_track.Location, frame);
videoPlayer = vision.VideoPlayer('Position', [100, 100, size(frame, 2),
size(frame, 1)]);
% Initialize array to store tracked points
tracked_points = [];
% Track the points from frame to frame
while hasFrame(videoReader)
frame = readFrame(videoReader);
[points, validity] = step(pointTracker, frame);
out = insertMarker(frame, points(validity, :), 'circle', 'Size', 30, "Color",
"red");
step(videoPlayer, out);
% Append points to the tracked_points array
tracked_points = cat(3, tracked_points, points);
end
% Release video player and tracker
release(videoPlayer); release(pointTracker);
pause(1); delete(videoPlayer);
xPos= squeeze(tracked_points(:, 1, :));
yPos= squeeze(tracked_points(:, 2, :));
```

Comparison of Experimental and Analytical Results Code - MATLAB

```
clear, clc, close all
load xm1
load TFp
xPos= xPos(:, 1:960);
xReal= xPos/scaleFactor;
time= [1:length(xReal)]/240;
xGround= xReal(5, :)- xReal(5, 1);
xTFvwd= lsim(TFvwd, xGround, time)+xGround';
xTFn= lsim(TFn, xGround, time)+xGround';
figure(), sgtitle("Prototype Motion")
subplot(2, 1, 1), hold on
plot(time, xGround, DisplayName= "Ground", LineWidth= 2)
plot(time, xReal(4, :)-xReal(4, 1), DisplayName= "Tracking", LineWidth= 2)
plot(time, xTFn, DisplayName= "Analytical", LineWidth= 2)
xlabel("time (s)"), ylabel("Position (cm)"), grid
title("no VWD"), legend(Location= "northwest"), a= axis;
subplot(2, 1, 2), hold on
plot(time, xGround, DisplayName= "Ground", LineWidth= 2)
plot(time, xReal(1, :)-xReal(1, 1), DisplayName= "Tracking", LineWidth= 2)
plot(time, xTFvwd, DisplayName= "Analytical", LineWidth= 2)
```

```
xlabel("time (s)"), ylabel("Position (cm)"), grid
title("with VWD"), legend(Location= "northwest"), axis(a)
figure(), sgtitle("Interstory Drift")
subplot(2, 1, 2), hold on
plot(time, xTFvwd-xGround', DisplayName= "with VWD", LineWidth= 2)
plot(time, xTFn-xGround', DisplayName= "no VWD", LineWidth= 2)
xlabel("time (s)"), ylabel("Column deflection (cm)"), grid
title("Analytical Results"), a= axis; legend
subplot(2, 1, 1), hold on
plot(time, [xReal(1, :)-xReal(1, 1)]-xGround, DisplayName= "with VWD", LineWidth=
2)
plot(time, [xReal(4, :)-xReal(4, 1)]-xGround, DisplayName= "no VWD", LineWidth= 2)
xlabel("time (s)"), ylabel("Column deflection (cm)"), grid
title("Experimental Results"), axis(a), legend
% AN
%[nMax, nMin]= localMaxMin(xTFn-xGround')
%[dMax, dMin]= localMaxMin(xTFvwd-xGround')
% EXP
[nMax, nMin]= localMaxMin([xReal(4, :)-xReal(4, 1)]-xGround)
[dMax, dMin]= localMaxMin([xReal(1, :)-xReal(1, 1)]-xGround)
nM= mean(nMax(1:6) - nMin(1:6)) % first 6 peaks
dM= mean(dMax(1:6) - dMin(1:6)) % first 6 peaks
100*abs((nM-dM)/nM)
```