

# **EFFICACY OF COMPLIANT TUNED LIQUID COLUMN DAMPERS (CTLCD) FOR SEISMIC VIBRATION CONTROL**

A Report Submitted in Fulfilment of the Requirement for the Award of the  
Degree of

**Master of Engineering in Structural Engineering**

Submitted by

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## DECLARATION


I, Arambam Chanu Nganthoibi, hereby declare that work which is presented in this report entitled “**Efficacy of Compliant Tuned Liquid Column Dampers (CTLCD) For Seismic Vibration Control**” as per the requirements for the award of **Master of Engineering in Structural Engineering**, submitted in the Department of Civil Engineering, Thapar Institute of Engineering and Technology (TIET), Patiala. This work is carried out by me under the guidance of **Dr. Trishna Choudhury, Assistant Professor, Department of Civil Engineering, Thapar Institute of Engineering and Technology, Patiala**. It is declared that this work is original and has not been submitted anywhere else for the award of any other degree or certificate.

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## CERTIFICATE

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## **ABSTRACT**

This thesis presents an experimental investigation into the seismic response mitigation of a three-story scaled building model using a Compliant Tuned Liquid Column Damper (CTLCD). The study begins with a comprehensive literature review covering the development and performance of passive vibration control devices, particularly Tuned Liquid Column Dampers (TLCDs), and their evolution into more advanced forms such as Tuned Liquid Column Ball Dampers (TLCBDs) and Compliant TLCDs. The review establishes the effectiveness of fluid-based damping systems and highlights the need for further exploration of compliant designs in short-period structures.

To evaluate the performance of the CTLCD, a series of shake table experiments were conducted using 43 ground motion records encompassing a wide range of seismic characteristics. Acceleration and displacement responses were recorded at each floor under both uncontrolled and controlled conditions. The structural responses were analyzed in terms of peak and Root Mean Square (RMS) values to capture both instantaneous and sustained motion. The results demonstrate that the CTLCD effectively reduces RMS responses, particularly at the upper stories where dynamic amplification is more significant. Although peak response reduction varied depending on the ground motion, substantial energy dissipation and control of prolonged vibrations were observed.

Correlation analyses and control efficiency calculations further revealed the CTLCD's nonlinear damping behavior and its greater influence on RMS reduction than on peak suppression. Time history plots confirmed reductions in amplitude and vibration duration, especially at the top floor. These findings affirm the CTLCD's potential as a passive control strategy for enhancing the seismic resilience of flexible, multi-story buildings and provide a foundation for future advancements in fluid-based damping technologies.

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## LIST OF SYMBOLS & ABBREVIATIONS

Symbol	Description
TLD	Tuned Liquid Damper
TLCD	Tuned Liquid Column Damper
STLCD	Sliding-Tuned Liquid Column Damper
CTLCD	Compliant Tuned Liquid Column Damper
TMD	Tuned Mass Damper
BI	Base Isolation system
PLCD	Pendulum Liquid Column Damper
CTD	Combined Tuned Damper
TLCBD	Tuned Liquid Column Ball Damper
TLCBSSD	Tuned Liquid Column Ball Spring Sliding Damper
TLCBSRD	Tuned Liquid Column Ball Spring Rolling Damper
MTMD	Multiple Tuned Mass Damper
MTLCD	Multiple Tuned Liquid Column Damper
MTLCBD	Multiple Tuned Liquid Column Ball Damper
SDOF	Single Degree of Freedom
SMA	Shape Memory Alloy
$\mu$	Mass Ratio
$\omega_L$	frequency of TLCB
$\omega_s$	Natural frequency of the structure
$R_{bt}$	Ball-to-tube diameter ratio
$\xi$	Tuning frequency ratio of spring-ball-attached
$\gamma$	Length ratio
B	Horizontal length
$\chi$	Tuning ratio
$\delta$	Head loss coefficient
P- $\Delta$	P-delta effect or second order effect
$\theta$	Drift sensitivity coefficient
$M$	Secondary structural mass (Damper mass)
$M_s$	Structural Mass
$K_s$	Structural stiffness

$C_s$	Structural Damping Coefficient
L	Liquid column length
FDDs	Flow damping devices
TSD	Tuned Sloshing Damper
O-TLCD	Omnidirectional Tuned Liquid Column Damper
LCVAs	Liquid Column Vibration Absorbers
TTLCD	Toroidal Tuned Liquid Column Damper
ETLCD	Embossed Tuned Liquid Column Damper
CLCBD	Circular Liquid Column Ball Damper
CLD	Compliant Liquid Damper
UC	Uncontrolled
C	Controlled

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# Chapter 1

## INTRODUCTION

### 1.1. Overview

In recent years, enhancing the seismic resilience of structures has become a key focus in structural engineering, driven by the increasing destruction and severity caused by the earthquakes worldwide. Among various passive vibration control techniques, Tuned Liquid Column Dampers (TLCDs) have gained prominence due to their simplicity, cost-effectiveness, and adaptability. A TLCD comprises a U-shaped tube partially filled with liquid, in which the horizontal movement of the fluid generates inertial forces that counteract structural vibrations. This sloshing effect provides a contracting force that reduces the amplitude of the vibration. The effectiveness of TLCD is determined by various parameters such as the orifice opening size which are usually fixed at the horizontal limb of the u-tube, amount of liquid and other damping mechanism.

To improve energy dissipation capabilities, researchers have introduced modifications to the conventional TLCD configuration. Some of the advancement is the Compliant Mechanism, moving orifice and many other hybrids. The TLCD is tuned so that its natural frequency aligns with the primary vibration frequency of the structure. This resonance tuning allows for maximum energy transfer from the structural motion into the liquid, where it is dissipated through a combination of viscous effects, frictional losses, and orifice damping. An orifice is often installed in the horizontal section of the TLCD to restrict fluid flow, increasing resistance and enhancing the damping effect. Unlike mechanical dampers, TLCDs do not require external power sources or complex components, making them cost-effective, low-maintenance, and robust in long-term operation. They are especially advantageous in tall or flexible structures where conventional dampers may be less effective or too expensive to implement.

#### *1.1.1 Technical Background and Research Importance*

The concept of Tuned Liquid Column Dampers (TLCDs) originates from the broader category of passive vibration control systems. Their development is rooted in the foundational principles of Tuned Mass Dampers (TMDs), which have been widely used to mitigate structural vibrations. A TMD typically consists of a secondary mass connected to the primary

structure via springs and dampers. When properly tuned to the natural frequency of the structure, it counteracts vibrations by moving out of phase with the structural motion. Although effective, TMDs come with certain limitations, including high costs, mechanical complexity, and ongoing maintenance due to their reliance on moving mechanical parts.

To overcome these limitations, fluid-based systems were developed, leading to the introduction of Tuned Liquid Dampers (TLDs). These use the motion of liquid to dissipate energy, offering simpler designs and lower maintenance. Among the most notable advancements in this category is the Tuned Liquid Column Damper (TLCD), which uses a U-shaped column partially filled with liquid. The motion of the fluid column generates inertial forces that oppose structural vibrations, while an orifice inserted in the horizontal section provides additional damping through flow resistance. The basic ideas of Tuned Liquid Column Dampers (TLCDs) are listed below:

**a) Efficient Energy Dissipation Mechanism**

The core function of a TLCD is to dissipate structural vibration energy through the motion of a liquid column. When a structure experiences dynamic excitation, the liquid oscillates within the U-shaped tube, and energy is dissipated via hydrodynamic resistance, frictional effects, and orifice damping. This helps in significantly reducing vibration amplitudes.

**b) Efficient Design and Economic Viability**

TLCDs are simple and had a practical design, easily integrated into new or existing structures without the need for complex installation procedures or specialized construction materials. Compared to more sophisticated damping systems such as tuned mass dampers (TMDs) or active control devices, TLCDs are significantly more affordable, making them particularly suitable for cost-sensitive applications, including retrofitting older buildings or use in developing regions.

**c) Flexible Design and Scalability**

TLCDs are highly adaptable and can be customized to suit a wide range of structural configurations, from low-rise buildings to high-rise towers and long-span bridges. Their design can be scaled to accommodate varying levels of damping demand by modifying fluid volume, tube dimensions, and damper placement.

**d) Enhanced Structural Safety and Adaptability**

By effectively controlling vibrations and reducing displacements and inter-story drifts, TLCDs contribute to the overall stability and safety of structures during seismic or wind events. This reduction in motion helps protect both structural integrity and the safety of occupants. TLCDs have been successfully applied in various civil engineering structures, including buildings, bridges, towers, chimneys, and offshore platforms. Their versatility makes them a universal solution for diverse vibration control needs.

#### **e) Recent Developments in Passive Vibration Control Systems**

In the field of passive vibration control system, many innovative techniques have introduced. The moving orifice instead of fixed orifice, compliant mechanisms for short period structures, and other innovative dimensions of liquid damper. Moreover, numerous improvements in the numerical and simulation techniques have enable more accurate predictions on the performance of the TLCDs.

In summary, TLCDs operate by transforming structural kinetic energy into fluid motion, which is then dissipated by hydrodynamic forces. Their simplicity, adjustability, and effectiveness have made them a popular solution for vibration control in buildings, bridges, and other infrastructure exposed to dynamic loading.

### **1.1.2 Seismic Vibration Control Techniques**

A Vibration damper is a mechanical device used to dissipate energy and control motion in systems by reducing vibrations, oscillations, or shocks. By absorbing or dissipating vibrational energy, they help improve performance, prevent damage, and enhance comfort. Vibration dampers are commonly used in various applications, including automotive suspensions, aerospace systems, machinery, and civil engineering structures like bridges and buildings. They play a crucial role in mitigating oscillations, reducing wear and tear, and enhancing the overall stability of systems subjected to dynamic forces. There are mainly three types of vibration damping systems: passive, active, and semi-active.

#### **a) Passive Vibration Techniques**

These passive control systems include base mechanisms that alter the natural period of the structure while absorbing energy through hysteretic or viscous damping and dissipating it effectively. Energy transfer devices, such as tuned mass and liquid dampers, are effective reducing vibrations by redistributing energy among the vibrating modes.

#### **b) Active Vibration Techniques**

Active damping involves using external power and sensors to actively control vibrations in real-time, offering precise and adaptive control. Active damping involves the use of actuators or control systems that can modify the damping characteristics of a system in real-time, as opposed to passive damping, which relies on fixed materials and structures to absorb energy.

#### **c) Semi-active Vibration Techniques**

A combine features of both passive and active damping systems, providing a controlled force without the high energy requirements of active systems. Unlike passive dampers, which have fixed properties, semi-active dampers can adjust their damping characteristics in response to external conditions. This adaptability allows them to optimize performance based on the specific dynamic loads acting on the structure. require significantly less energy compared to fully active systems, making them more cost-effective and easier to implement

#### **d) Hybrid Vibration Techniques**

An Integration of multiple control techniques to achieve optimal seismic vibration control, hybrid systems are the combination of passive, active and semi-active components, aiming to provide better damping and control energy dissipation.

Dampers such as Tuned Mass Dampers (TMDs) and Tuned Liquid Column Dampers (TLCDs) have been installed in numerous tall structures worldwide to mitigate excessive vibrations caused by wind, seismic activity, and occupant movement. In many instances, these devices were added after construction as retrofitting measures to address unexpected building sway and occupant discomfort. For example, the John Hancock Tower in Boston faced severe wind-induced vibrations and was retrofitted with two 300-ton TMDs, while the Sofitel Hotel (formerly Hotel Cosima) in Tokyo became the first to install a TLCD in 1994. Similarly, the Millennium Bridge in London had to be fitted with dampers to correct problematic lateral movements caused by synchronized pedestrian steps. In contrast, several modern skyscrapers have integrated dampers into their design from the outset. Taipei 101 in Taiwan features a 660-ton TMD that reduces motion during typhoons and earthquakes, and the Comcast Center in Philadelphia houses the world's largest TLCD to control sway in its slender frame. Other notable examples include One Wall Centre in Vancouver, which uses TLCDs, and the St. Francis Shangri-La Place in Manila, which pioneered the use of viscous dampers to reduce vibrations efficiently without occupying significant space. These applications underscore the growing importance of dynamic response control in contemporary high-rise design.

## 1.2. Objectives of the Study

The primary objective of this research is to implement a Compliant Tuned Liquid Column Damper (CTLCD) in a short-period structure representative of low- to medium-rise buildings, with a target fundamental time period of approximately 0.3 seconds. This involves experimental testing using a scaled structural model, fabrication of a U-tube system, and the design of an optimized compliant mechanism that ensures effective energy dissipation along with self-centering capability.

The specific objectives of the study are as follows:

- To design and develop a reliable CTLCD system incorporating a U-tube integrated with a dynamic orifice, enabling both efficient damping and self-centering behavior through a compliant mechanism.
- To experimentally evaluate the seismic performance of a short-period structure with and without the CTLCD based on shake table test using recorded earthquake ground motions.
- To determine the control efficiency and investigate the relationship between peak and RMS responses for a comprehensive understanding of the CTLCD's damping effectiveness enabling the assessment of the applicability and effectiveness of the CTLCD in enhancing seismic resilience for short-period structures.

## 1.3. Layout of the Thesis

This thesis is structured into five chapters, each focusing on a distinct aspect of the research concerning the development and performance evaluation of Tuned Liquid Column Dampers (TLCs) for seismic vibration control.

- *Chapter 1 – Introduction:*

Provides a general background on structural vibration control with a focus on TLCs. It also presents the objectives, and scope of the present study.

- *Chapter 2 – Literature Review:*

Reviews relevant research conducted by various scholars on the development, optimization, and application of TLCs and similar passive control devices are discussed. Detail studies on their efficiency, innovative configurations, and role in enhancing seismic performance are carried out.

- *Chapter 3 – Methodology:*

Describes the experimental and analytical methodologies adopted in the study, detailing the design, fabrication, and testing procedures of the proposed compliant mechanism-based TLCD system.

- *Chapter 4 – Results and Discussion:*

An analysis of the experimental data is presented, followed by a discussion of its implications for the structural performance of the system under seismic loading.

- *Chapter 5 – Conclusions and Future Scope:*

Summarizes the key conclusions derived from the research, outlines the major contributions of the study, and proposes potential avenues for future research in the field of passive vibration control.

## Chapter 2

### LITERATURE REVIEW

#### 2.1. Overview

The present chapter an overview of various passive vibration damping devices used for seismic vibration control in structures, including Tuned Liquid Dampers (TLDs), Tuned Liquid Column Dampers (TLCDs), Sliding Tuned Liquid Column Dampers (STLCDs), Tuned Mass Dampers (TMDs), and base isolation (BI) systems. Particular emphasis is placed on exploring the potential of Compliant Tuned Liquid Column Dampers (CTLCDs). The chapter also reviews previous studies related to these devices and evaluates their effectiveness in mitigating seismic vibrations.

#### 2.2. Passive Vibration Techniques

Passive vibration techniques are those that doesn't use any external input to mitigate the vibration. These vibration control dampers adjust the natural time period of the structure while absorbing the energy through hysteretic or viscous damping and dissipating it effectively. Use of vibration control dampers started since 1960s, engineers used this passive control vibration devices to control the building moment during earthquake or strong winds. There are mainly three types of passive vibration control dampers which are added dampers, absorbers and isolators. Added dampers are installed between the two points inside the structure where relative motion is expected during seismic or dynamic loading (Symans *et al.* 2008). Absorbers are those which goes out-of-phase from the structure to mitigate the structural vibration. Isolators are devices installed between the foundation and the superstructure, designed to alter the transmission path of seismic energy. They effectively dissipate or redirect a significant portion of the input energy before it reaches the main structural system. (Nochebuena-Mora *et al.* 2021; Sheikh *et al.* 2022).

These devices effectively reduce structural vibrations by redistributing energy among different vibration modes, thereby enhancing structural control during seismic events. They dissipate seismic energy by converting kinetic energy into heat or by transferring it across various modes of vibration, thus significantly reducing the impact of lateral loads on the

structure. Nevertheless, these are successfully applied in civil structures to enhance damping, stiffness, and strength. Resonance occurs when the frequency of an external excitation, such as an earthquake, matches the natural frequency of a structure, resulting in large amplitude vibrations that can cause significant structural damage.

However, in spite of their effectiveness the isolators and added dampers have certain limitations. Base isolators normally require large displacement capacities and adequate clearance, which can be challenging in retrofitting or space-constrained sites. Moreover, their long-term durability, especially for elastomeric materials, can be affected by aging and environmental conditions, requiring ongoing maintenance. On the other hand, added dampers that enhance energy dissipation may lead to increase design complexity, construction cost, and sometimes floor accelerations, especially if not properly tuned. In both cases, performance is highly sensitive to device placement and parameter selection, which demands careful engineering and analysis.

The following sections briefly discuss about the various passive vibration control absorbers used. This includes tuned mass dampers, tuned liquid damper, and tuned liquid column damper as illustrated in Figure 2.1. The present study is however, mainly focused on Tuned Liquid Damper devices used worldwide, specifically on the Tuned Liquid Column Dampers and its variations using compliant mechanisms.

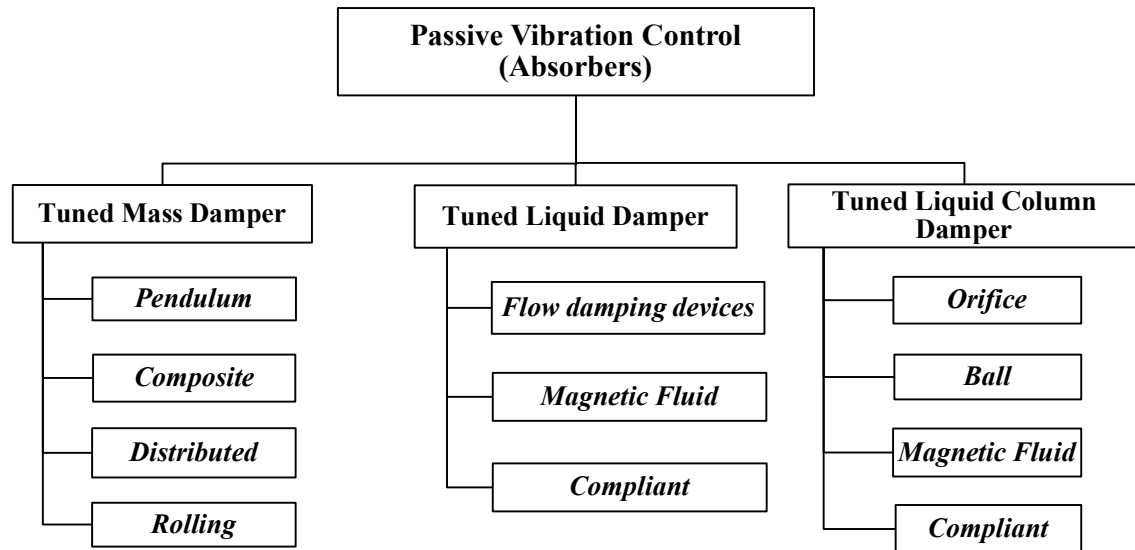


Figure 2.1: Flowchart describing different forms of passive vibration control devices.

### 2.2.1. Tuned Mass Dampers (TMD)

Tuned Mass Dampers (TMDs) have been extensively studied since the 1990s, building upon classical TMD technology developed as early as the mid-20th century. The foundational work by researchers such as Ormondroyde and Den Hartog (1928); Den Hartog (1956); Brock (1946); Thomson and Dahleh (1988); Ghosh and Basu (2007) laid the groundwork for modern TMD applications. A traditional system, illustrated in Figure 2.2 dissipates vibratory energy by coupling a secondary structural mass ( $M$ ) to a primary structural mass ( $M_s$ ) through a spring for stiffness ( $K_d$ ), and a damper ( $C_d$ ). The TMD is calibrated to resonate at a specific frequency, usually the fundamental frequency of the structure. During structural vibrations, the TMD oscillates out of phase with the motion, thereby dissipating energy and effectively reducing the amplitude of the structural response.

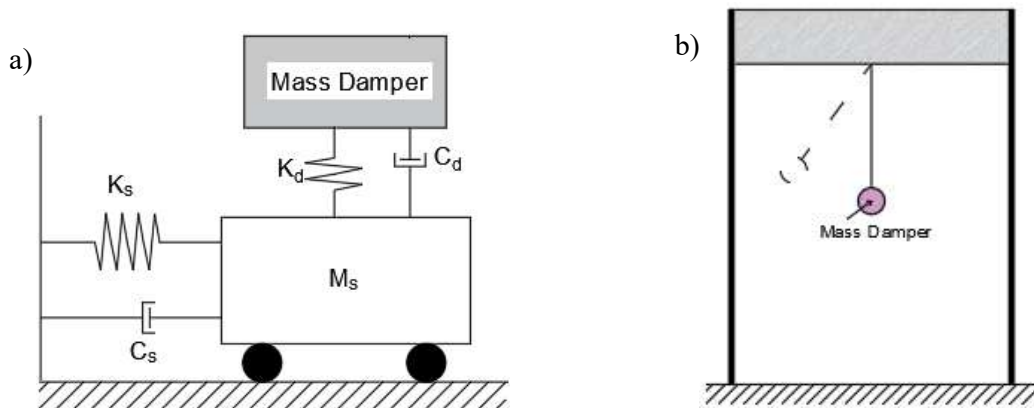


Figure 2.2: (a) Tuned Mass Damper (b) Pendulum Tuned Mass Damper

There are mainly four types of tuned mass dampers - pendulum tuned mass damper, composite tuned mass damper, distributed tuned mass damper and rolling tuned mass damper. In pendulum-type TMDs, the mass is suspended from a cable or rod, allowing it to swing and counteract structural motion through pendular action. This mass counteracts the motion during wind and seismic excitation (Gutierrez Soto and Adel 2013; Yang *et al.* 2022). Composite tuned mass damper is modified from classical TMDs, it consists of series or parallel, and different modal frequencies of the main structure (Yang *et al.*, 2022). The distributed tuned mass damper consists of several small TMDs instead of one TMD which are usually placed (Yang *et al.* 2022). In rolling tuned mass damper a heavy ball rolls without slipping inside a moving spherical recess, helping to absorb vibrations through combined rolling and body motion (Legeza 2002; Matta 2019; Liu *et al.* 2025). Koutsoloukas *et al.* (2022) have also present a comprehensive review of global trends in mass damper systems for buildings,

revealing a notable disparity between academic research developments and their adoption in industry practices.

TMDs has a well-established technology and are successfully implemented on real life structures such as Taipei 101, one of the tallest skyscrapers in the world, located in Taiwan; John Hancock Tower, Boston USA; Citigroup Center in New York City, USA; Tokyo Skytree in Tokyo, Japan; and many more. While TMDs are effective in reducing structural vibrations caused by wind or seismic activity, they also have some limitations. These include high installation and maintenance costs, the need for significant space (especially in tall buildings), limited effectiveness across multiple vibration modes, and reduced performance under unpredictable or extreme dynamic loads, such as large earthquakes (Gutierrez Soto and Adeli 2013).

### 2.2.2. Tuned Liquid Damper (TLD)

TLD utilize the motion of liquid within a container to counteract structural vibrations (Figure 2.3). When the structure experience vibrates due to wind or earthquake, the slosh of the liquid moves out of phase with the buildings motion.

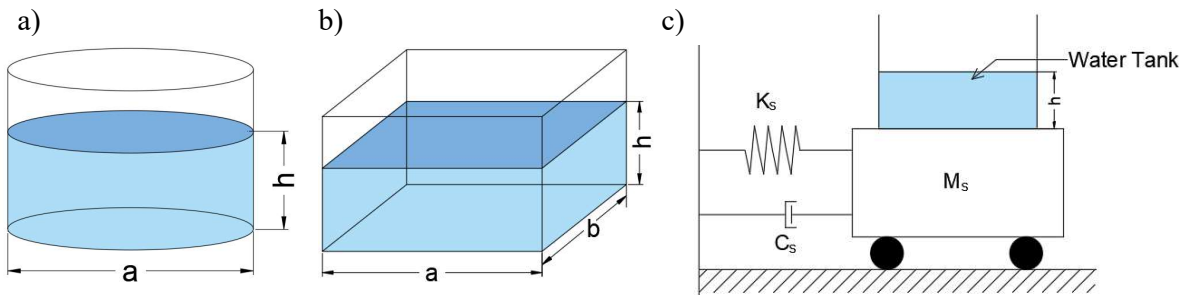


Figure 2.3: (a) Circular TLD tank, (b) Rectangular TLD tank, and (c) Idealized Single Degree of Freedom (SDOF) system model with a TLD.

The fundamental dynamics of liquid in laterally excited deep tanks can be effectively captured using the simplified mechanical model developed by Graham and Rodriguez (1952), which represents the liquid as a combination of impulsive mass moving with the container and convective masses accounting for sloshing behavior. Building on the need for better TLD damping, Fujino *et al.* (1988) experimented with rough-bottom and closed-roof tanks, which proved inadequate, prompting further research into flow damping devices (FDDs). Early real-world applications of TLDs with FDDs emerged in Japan in the 1990s for structures like the Sakitama and Ikuchi bridges and the Tokyo airport control tower. Prominent building applications include One King West (Toronto), One Rincon Hill (San Francisco), and The

Independent (Austin). However, seismic applications remain untested due to mismatched structural periods. Vázquez-Greciano *et al.* (2024) reviewed FDD types including nets, screens, and baffles. Habenberger (2015) highlighted that damping arises from wall friction, bottom in shallow tanks, sidewalls in deep ones, while wave breaking at high amplitudes further enhances dissipation. Tail *et al.* (2002) showed that adding horizontal slats increased damping nonlinearity, and screens helped maintain linear behavior and improve internal damping.

Vázquez-Greciano *et al.* (2024), also wrote a review on effectiveness for using various types of magnetic fluids. The magnetic fluid enhance the damping capabilities when exposed to the magnetic field by increasing its viscosity. Many other researches (Horie *et al.* 2007; Sakamoto *et al.* 2001; Konar and Ghosh 2021; Genc and Derin 2012) investigated on various magnetic field over the years. Some researchers have (Sarkar and Fitzgerald (2024); Prakash and Jangid 2022) also introduced an innovative system called the Tuned Mass Damper Fluid Inerter, which significantly enhances wind-induced vibration control in tall buildings while requiring minimal mass and stroke. The traditional TMD continues to be widely applied in civil engineering structures, including buildings, bridges, tall towers, and offshore platforms (Wang *et al.* 2023; Wang *et al.* 2019; Charmpis *et al.* 2012; Moutinho 2012). Nevertheless, due to its high cost of this smart fluids, requirement of continuous power supply to activate and control the magnetic fields and magnetic systems makes it less feasible.

Comparative tests between the TMD and TLD were also carried out, revealing that TLDs provide comparable or superior performance in vibration control, especially under amplitude-dependent conditions. (Tait *et al.* 2002; Konar 2024; Wu *et al.* 2024). One of the key advantages is their dual functionality, many buildings already include such tanks (e.g., overhead water tanks, firefighting reservoirs, or ice thermal storage units) for other purposes, and utilizing them as dampers eliminates the need for separate installations. This makes them highly cost-effective, with studies showing installation costs as low as 0.03%–1.0% of the total construction cost, compared to around 2.6% for conventional tuned mass dampers (TMDs). When properly equipped with flow damping devices (FDDs) such as nets, baffles, or floating roofs, deep tanks can achieve comparable damping performance to shallow tuned liquid dampers (TLDs), especially in stiffer structures where shorter sloshing periods are more effective (Konar and Ghosh, 2022).

However, there are several limitations to consider. Deep tanks generally contain a large proportion of impulsive liquid mass that moves in unison with the structure, thereby

contributing minimally to sloshing-induced energy dissipation. Moreover, they have low inherent damping in their natural state, making them less effective without additional damping devices. Only the upper portion of the liquid participates in sloshing, further limiting performance. Fluctuations in liquid level can also impact tuning, although this can be mitigated by maintaining a liquid depth ratio ( $h/L$ ) greater than 0.5 (Konar and Ghosh, 2022). Furthermore, while the idea of semi-active systems, with adjustable FDDs or spring stiffness is promising, such technologies are still in development and may involve additional complexity. Despite these challenges, with thoughtful design and innovative modifications, deep tanks remain a viable and economical option for vibration mitigation in many structural applications.

### ***2.2.3. Tuned Liquid Column Damper (TLCD)***

Tuned Liquid Column Dampers (TLCDs) consist of a U-shaped tube partially filled with liquid, featuring an orifice in the horizontal section to resist the motion of the liquid, as illustrated in Figure 2.4. Similar to Tuned Liquid Dampers (TLDs), when the structure undergoes vibration, the liquid oscillates within the tube. The orifice introduces resistance, providing damping by dissipating the energy of the moving liquid. The system is tuned to the natural frequency of the structure, enabling the liquid motion to effectively counteract the structural vibrations. Researchers have developed many other new damping techniques such as Tuned Liquid Column Ball Dampers (TLCBDs), Tuned Liquid Spring Sliding Ball Dampers (TLCSSBDs), and Tuned Liquid Spring Rolling Ball Dampers (TLCSRBDs), as reported by Al-Saif *et al.* (2011), Shah *et al.* (2021), and Pal *et al.* (2020). Additionally, studies by Colwell and Basu (2008) have explored the effectiveness of water viscosity on damping performance. And many other new inventions are carried out, which will be discussed below on these innovative damping systems, their working mechanisms, comparative efficiency, and potential applications in structural engineering will be presented in the following sections.

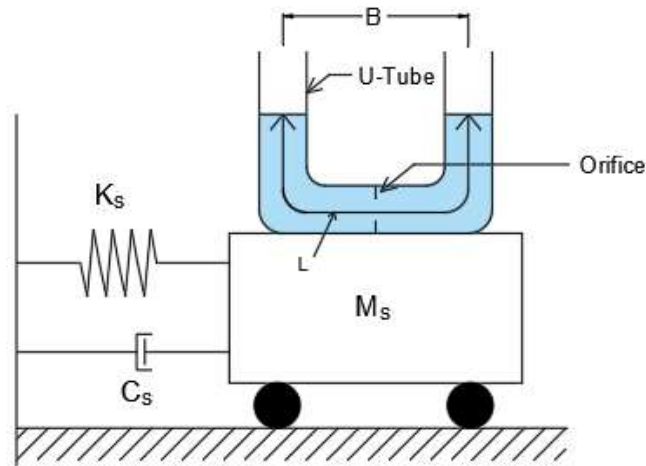


Figure 2.4: Schematic diagram of TLCD

The use of magnetic fluids in TLCDs liquid has also been explored by several researchers (Cheng *et al.*, 2015; Masuda *et al.*, 2013; Roychowdhury and Gur, 2022; Banerjee *et al.*, 2025), who investigated their potential to enhance damping performance through tuneable viscosity and adaptive control under applied magnetic fields.

Tuned Liquid Column Dampers (TLCDs) have been successfully implemented in several real-world structures to enhance performance and stability under wind loading. The first application was in the Hotel Cosima in Tokyo, Japan, completed in 1994. Since then, TLCDs have been installed in numerous iconic buildings worldwide. Notable examples include the Comcast Center in Philadelphia, USA, and One Wall Centre, a 48-story landmark in Vancouver, Canada. In New York City, the Random House Tower, a 52-story mixed-use skyscraper, also employs TLCD technology. In South Korea, the First World Towers in the Songdo International Business District of Incheon, completed in 2009, marked a significant application of TLCDs in a large-scale development. Another example is 461 Dean Street (also known as the B2 Tower) in Brooklyn, New York. Over time, various configurational adaptations of the TLCD have also been developed and implemented in buildings to further improve vibration control performance (Konar *et al.*, 2024).

#### 2.2.4. Compliant Liquid Dampers (CLD)

The main idea to make the mechanism compliant is to improve the tuning on short-period (stiff) buildings. In short-period structures, the natural frequency of TLDs might end up being too high for liquid sloshing effect to match effectively. This implies the need for a very small tank or shallow liquid depth in the TLD to achieve the required frequency, and these configurations are ineffective or impracticable for implementation. As small tanks don't have

enough mass or volume to generate a significant damping force. When the liquid cannot effectively resonate with the building's motion, the TLD loses efficiency. The damping is reduced, and the TLD becomes less effective in controlling structural vibrations.

Unlike the conventional TLDs or TLCDs, compliant mechanism in the TLD and TLCD achieves broader applicability by using flexible connections, which eliminate the need to tune the damper directly to the structural frequency. CTLCDs have two degrees of freedom (DOF), one for the damper's motion relative to the structure, and one for the liquid oscillation. Even when the system is not perfectly tuned to the structure's natural frequency, the liquid continues to oscillate and still supplies effective damping. A comparison of the various aspects of TMD, TLD, and TLCD are shown in the Table 2.1. Detailed discussion on TLCDs and the compliant mechanism are discussed separately in the following sections.

Table 2.1: Comparison between TMD, TLD, and TLCD

<b>Feature</b>	<b>TMD</b>	<b>TLD</b>	<b>TLCD</b>
<b>Working Principle</b>	Uses solid mass connected to spring and dashpot	Uses Sloshing of liquid in a container	Uses U-shaped liquid column motion with orifice damping
<b>Energy Dissipation</b>	Through mechanical damping (dashpot)	Through fluid motion and viscosity	Through fluid motion and orifice-induced damping
<b>Performance</b>	Highest damping performance overall	High mass effect, moderate damping	Balanced damping and mass contributions
<b>Sensitivity to tuning</b>	Highly sensitive to frequency mismatch	Less sensitive than TMD	Moderately sensitive
<b>Mass Contribution</b>	Moderate	High	Moderate-to-High
<b>Advantages</b>	<ul style="list-style-type: none"> <li>• High damping performance</li> <li>• Widely studied and implemented</li> <li>• Reliable for tall buildings</li> </ul>	<ul style="list-style-type: none"> <li>• Can use existing water tanks</li> <li>• Low maintenance</li> <li>• Useful dual purpose (e.g., water supply &amp; damping)</li> </ul>	<ul style="list-style-type: none"> <li>• Good balance of mass and damping effects</li> <li>• Easy to tune via column dimensions and orifice</li> <li>• Compact design</li> </ul>
<b>Limitations</b>	<ul style="list-style-type: none"> <li>• Requires precise tuning</li> <li>• Heavy and takes more space</li> <li>• More complex mechanically</li> </ul>	<ul style="list-style-type: none"> <li>• Lower damping than TMD</li> <li>• Sensitive to water depth and container shape</li> <li>• Needs regular fluid management</li> </ul>	<ul style="list-style-type: none"> <li>• Orifice can clog</li> <li>• More complex than TLD</li> <li>• Requires space for U-shaped column setup</li> </ul>
<b>Best Use Cases</b>	<ul style="list-style-type: none"> <li>• High-rise buildings</li> </ul>	<ul style="list-style-type: none"> <li>• Medium-rise buildings</li> </ul>	<ul style="list-style-type: none"> <li>• Mid-rise buildings</li> </ul>

	<ul style="list-style-type: none"> <li>• Where mechanical maintenance is acceptable</li> </ul>	<ul style="list-style-type: none"> <li>• Retrofits using water tanks</li> <li>• Where simplicity is prioritized</li> </ul>	<ul style="list-style-type: none"> <li>• Where both damping and sloshing mass effects are useful</li> </ul>
<b>Structural Sensitivity</b>	Highly sensitive to tuning errors	Less sensitive, but still needs tuning	Moderately sensitive
<b>Installation Complexity</b>	High (mechanical setup with moving parts)	Low to moderate	Moderate (requires U-tube, orifice, and correct filling)
<b>Maintenance Needs</b>	Medium to high (mechanical wear and tear)	Low (mostly fluid management)	Moderate (fluid + orifice condition)
<b>Cost</b>	Higher (custom fabrication often needed)	Lower (can reuse tanks, fewer mechanical parts)	Moderate (requires specialized container design)

## 2.3. Tuned Liquid Column Dampers (TLCD)

### 2.3.1. Introduction to the TLCDs

TLCDs are passive vibration control systems known for their simplicity, adaptability, and effectiveness in mitigating structural vibrations caused by dynamic loads such as wind and earthquakes. First introduced by Sakai *et al.* in 1989, a TLCD consists of a U-shaped column partially filled with liquid, featuring an orifice in the horizontal section. Vibrational energy is dissipated through the oscillatory motion of the liquid and head loss as it passes through the orifice (Figure 2.4). TLCDs are relatively easy to tune, with key control parameters including the length of the liquid column, which governs the system's natural frequency, and the orifice opening, which adjusts the damping capacity. This mechanism provides a straightforward yet highly effective means of passive vibration control.

Past research (Gao *et al.* 1997; Hochrainer 2005; Karimi *et al.* 2018; Aydemir *et al.* 2024; Tran *et al.* 2024) have also experimented on various shapes of TLCDs, such as U-shaped, V-shaped, 60° or 45° elbow, to optimize performance for different applications. For example, V-shaped TLCDs have been shown to provide superior damping effects under strong wind vibrations (Gao *et al.* 1997; Tran *et al.* 2024; Karimi *et al.* 2018). Moreover, the 45° elbow could enhance seismic response mitigation by 25% compared to normal U-TLCDs (Aydemir *et al.* 2024). Also, TLCDs are relatively inexpensive compared to other passive dampers like TMDs. They require minimal maintenance, have no moving mechanical parts, and can be easily installed into existing structure. The various features of the TLCDs are discussed in the subsequent sections.

A new technique was introduced by Vafaei *et al.* (2021), where a submerged pendulum is used inside the deep container to break the waves and allows a hybrid TMD-TSD system. Park *et al.* (2018) also introduced embossments on the inner surface of TLCD known as Embossed Tuned Liquid Column Damper (ETLCD). The water surface response was primarily measured using a laser distance sensor, as given in Figure 2.5.

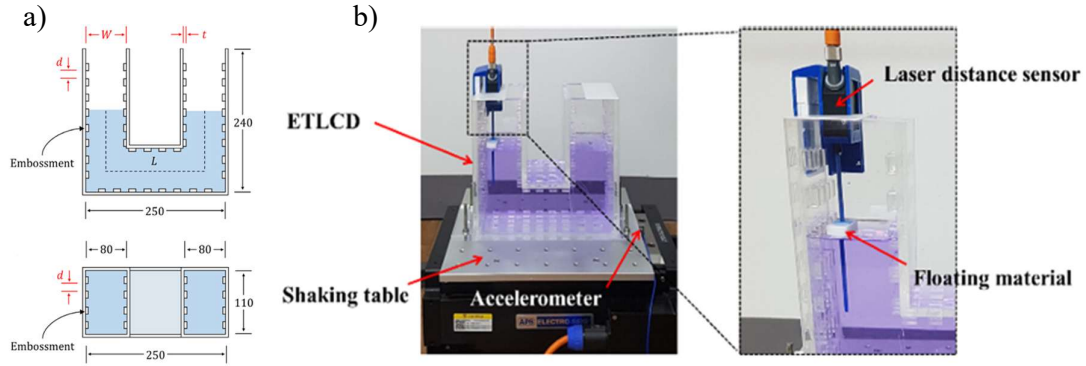


Figure 2.5: (a) Dimension of an ETLCD specimen and (b) Test set up of the characteristic experiment. (Park *et al.* 2018)

It was seen that ETLCD exhibited superior vibration control performance compared to conventional TLCDs. The performance was evaluated in terms of response reduction, damping efficiency, and system stability. The study also found that the natural frequency observed during experiments was 8-15% higher compared to theoretical calculation, this was because of the water in the physical system behaves differently than theoretical assumptions. Also, the damping ratio of ETLCD was 1.6 times higher than TLCD. ETLCD achieved damping values between 2.6% and 17.8%, whereas TLCD achieved only 1.5% to 6.5%.

A modified form of the TLCD, known as the Liquid Column Vibration Absorber (LCVA), was introduced by Hitchcock *et al.* (1997a). This system offered enhanced flexibility by allowing the vertical and horizontal columns to have different cross-sectional areas. This enabled better frequency tuning. The concept was further developed in subsequent works (Hitchcock *et al.* 1997b; Lee *et al.* 2011; Rozas *et al.* 2016; Ding *et al.* 2024), exploring various TLCD configurations, including a bidirectional design. These studies demonstrated how geometric adjustments could enhance vibration suppression (Figure 2.6(a), (b)). Smith *et al.* (2005) also modified the TLCD using different cross-sectional areas, as shown in Figure 2.6(c).

Additionally, Zeng *et al.* (2014) designed S-shaped TLCDs to increase the effective length without occupying excessive horizontal space (Figure 2.6(d)). Mehrkian and Altay (2020) introduced the Omnidirectional Tuned Liquid Column Damper (O-TLCD), an arrangement of multiple L-shaped liquid columns around a central joint. This design effectively reduces vibrations from any horizontal direction, making it well-suited for structures subjected to random excitations such as wind or earthquakes (Figure 2.6(e)). A detailed study on O-TLCDs was later conducted by Mehrkian and Altay (2022) and Zimmer *et al.* (2022)

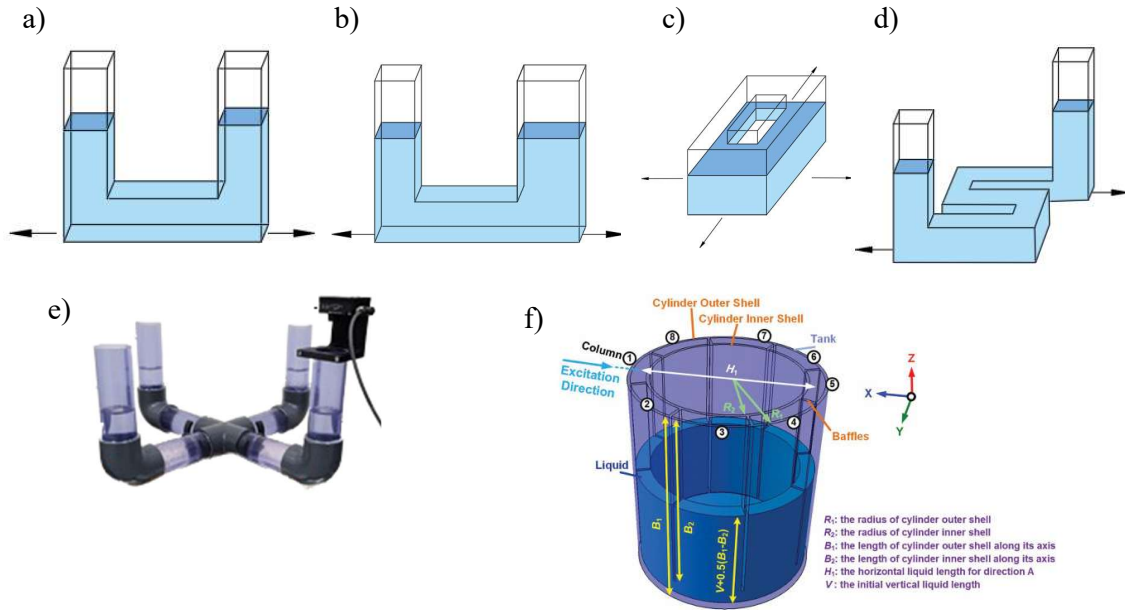


Figure 2.6: Variations on the TLCD container shape, a) unidirectional LCVA (Hitchcock *et al.*, 1997a), b) bidirectional LCVA (Hitchcock *et al.*, 1997b), c) asymmetric LCVA (Smith *et al.*, 2005), d) S-shaped TLCD (Zeng *et al.*, 2014) e) O-TLCD (Mehrkian and Altay, 2020) and f) TTLCD (Ding *et al.* 2022)

Recently, a multidirectional vibration control device, the Toroidal Tuned Liquid Column Damper (TTLCD), was developed to overcome the limitations of traditional TLCDs. Its circular configuration is ideal for applications like wind turbines and buildings, enabling effective damping in all lateral directions. Studies by Ding *et al.* (2020, 2021, 2022, 2023) and Younes (2025) demonstrate the TTLCD's effectiveness under seismic, wind, and wave loads. Both theoretical and experimental analyses confirm the TTLCD's strong performance, simplified bidirectional modelling, and optimized design parameters, making it a compact and efficient solution for multidirectional vibration suppression.

A sealed tuned liquid column damper was introduced which offers enhanced flexibility for vibration control through frequency tuning by adjusting air volume, pressure, and geometry. Reiterer and Ziegler, (2005) highlighted the benefits of air spring effects in extending TLCD applicability, while Hochrainer and Ziegler (2006) proposed practical guidelines for optimal placement and tuning. Studies have demonstrated sealed-TLCD's effectiveness across diverse applications, from reducing wind-induced vibrations in cable-stayed bridges (Shum *et al.*, 2008) to mitigating seismic effects in offshore platforms and torsional vibrations in asymmetric structures. Bhattacharyya *et al.* (2017a) experimentally validated the nonlinear air spring behavior, showing that it can be approximated using equivalent linear stiffness for simplified

yet accurate design. Younes (2019) further confirmed its superior performance over conventional TLCDs, especially in space-constrained scenarios. The adaptability of sealed TLCDs has led to their application in various dynamic environments. Notably, Liu *et al.* (2024) proves the effective for frequency tuning through linearized air spring stiffness, particularly in low-frequency structures with varying sealing conditions.

### **2.3.2. Working Mechanism of the TLCDs**

The liquid in the TLCDC oscillates to dissipate the energy experience on the structure. This motion is due to the inertial forces acting on the liquid as the structure moves. Energy is dissipated due to head loss as the liquid flows through the orifice located in the horizontal section of the TLCDC. This head loss is a result of the resistance encountered by the liquid as it passes through the orifice, converting kinetic energy into heat. The natural frequency of the liquid column is adjusted to align with the dominant frequency of the structure for optimal vibration mitigation. This tuning ensures that the TLCDC can effectively counteract the structural vibrations by maximizing energy dissipation at the resonant frequency. Gravity serves as the primary restoring force, returning the liquid to its equilibrium position after each oscillation. This restoring force is crucial for sustaining the oscillatory motion of the liquid. Combined with energy dissipation caused by head loss as the liquid flows through the orifice, gravity contributes to the overall damping effect of the TLCDC system. This effect reduces the amplitude of structural vibrations, thereby enhancing the stability and safety of the structure.

### **2.3.3. Control Parameters of the TLCDCs**

The parameters that influence the control and function of TLCDCs are mainly, tuning frequency ratio, orifice opening ratio, mass ratio, cross-sectional area of the column, total length of the liquid column, and the damping ratio.

#### **a) Tuning frequency ratio**

The tuning ratio is defined to be the ratio of the natural frequency of the tuned liquid column damper ( $\omega_L$ ) to that of the structure ( $\omega_S$ ), as given in Eq. 2.1. For optimal control performance, a tuning ratio close to 1 is typically preferred, ensuring that the TLCDC effectively counteracts the structural vibrations.

$$\text{Tuning Ratio} = \frac{\omega_L}{\omega_S} \quad (\text{Eq. 2.1})$$

Tuning of the TLCD with the structure is very important as they influence the TLCD effectiveness in damping. Proper tuning implies that the damper's natural frequency is aligned with the structure's natural frequency or the targeted vibration mode, allowing the damper to effectively absorb and dissipate vibrational energy. It is likely that a damper that has not been tuned may not perform at an optimal level, and so would not be capable of holding down the level of vibratory motion to zero, hence letting the structure sway too freely in dynamic loads, such as earthquakes or even wind load. Typical range of tuning is between 0.95 to 1.05. Cao (2025) analyzed sensitivity of the TLCD devices being mistuned, with a highest sensitivity to mistuning in the larger mass components comparatively to the tuned mass dampers. If the mistuning gets beyond  $\pm 15\%$  it can lead to significant performance degradation.

**b) Orifice Opening Ratio**

The orifice in a TLCD provides damping by controlling the energy dissipation through the oscillating liquid column. A larger head loss corresponds to increased damping, meaning more resistance to liquid flow. Nevertheless, too much head loss can reduce damping effectiveness because the liquid doesn't oscillate enough to absorb energy. The orifice opening can be adjusted to regulate the level of damping applied to the structure, allowing for control over the energy dissipation characteristics of the TLCD.

$$\text{Orifice opening ratio} = \frac{\text{Effective open are of the orifice}}{\text{Cross-sectional area of the column or tube}} \quad (\text{Eq 2.2})$$

According to Balendra *et al.* (1995), when the orifice opening ratio is small, particularly below 0.5, the system experiences higher damping. Conversely, a larger opening ratio results in reduced damping, thereby lowering the TLCD's effectiveness in vibration control. Optimal performance is achieved by balancing turbulence and viscous damping, particularly under varying excitation amplitudes. Typically, it ranges from 0.1 to 1.0.

**c) Ball-to-tube diameter ratio ( $R_{bt}$ )**

In place of fixed orifice, researchers have introduced a moving orifice on the TLCD known as Tuned Liquid Column Ball Damper (TLCBD). A movable ball is placed in the horizontal limb of the TLCD in place of a fixed orifice, allowing it to move freely and dynamically regulate the flow resistance.  $R_{bt}$  influences the resistance that the ball adds to the system (Damping ratio increases with increasing  $R_{bt}$ ).

$$\text{Ball-to-tube diameter ratio } (R_{bt}) = \frac{\text{Diameter of the ball } (d_b)}{\text{Inner diameter of the tube } (d_t)} \quad (\text{Eq 2.3})$$

The optimal ball diameter was found to be approximately 0.8 of the height of the horizontal section. (Al-Saif *et al.* 2011).

**d) Tuning frequency ratio of spring-ball-attached ( $\xi$ )**

$$\text{Tuning frequency ratio of spring-ball-attached } (\xi) = \frac{\text{Frequency of spring ball system } (\omega_{bs})}{\text{Natural frequency of the structure } (\omega_s)} \quad (\text{Eq 2.4})$$

For optimal performance of a Tuned Liquid Column Spring Sliding Damper (TLCSSD),  $\xi$  should be 1.4 and in the case of a Tuned Liquid Column Spring Rolling Damper (TLCSRD),  $\xi$  should be 1.6 for best results (Shah *et al.* 2022).

**e) Mass Ratio ( $\mu$ )**

The mass ratio is defined as the ratio of the liquid mass in the TLCD to the total mass of the structure. A higher mass ratio generally results in improved damping performance (Gao *et al.*, 1997), as the increased liquid mass provides greater inertia, thereby enhancing the system's ability to oppose and dissipate structural motion. This enhanced inertia improves energy absorption and overall damping performance. Conversely, a lower mass ratio results in reduced damping effectiveness. Al-Saif *et al.* (2011) suggests a selection within 0.005–0.05, and other researchers like Gao *et al.* (1997) and Shum (2009) confirm that  $\mu$  of 0.03–0.05 provides optimal vibration control.

$$\text{Mass ratio } (\mu) = \frac{\text{mass of liquid } (m_d)}{\text{mass of the structure } (m_s)} \quad (\text{Eq 2.5})$$

A commonly adopted value is 0.03 (3%), which has been shown to deliver high damping efficiency while maintaining manageable requirements in terms of additional weight and volume. Selecting a mass ratio of 3% ensures that the TLCD or TLCBD effectively reduces structural vibrations without introducing impractical challenges related to space, cost, or structural modification (Al-Saif *et al.* 2011).

**f) Length ratio ( $\gamma$ )**

The length ratio is defined as the ratio of the horizontal length ( $B$ ) to the total length ( $L$ ) of the liquid column in the TLCD, as shown in Equation (2.7). This ratio influences the natural frequency of the liquid's sloshing motion and plays a key role in the tuning of the system. Higher  $\gamma$  results in more liquid sloshing which results in more damping. Whereas, lower  $\gamma$  means less horizontal moment, so lesser damping.

$$\text{Length ratio } (\gamma) = \frac{\text{Horizontal length } (B)}{\text{Total length } (L)} \quad (\text{Eq 2.6})$$

A longer horizontal section allows more liquid movement, which creates greater inertia and energy dissipation. If  $\gamma$  gets too high (like 0.95), the vertical columns become too short, reducing the gravitational restoring force that helps the fluid oscillate efficiently. But if it becomes too low, say less than 0.6 then the vertical sections are too long, restricting the fluid movement and reducing damping. For an economical and efficient design, the length ratio should typically lie within the range of 0.7 to 0.9 (Shum 2009).

Overall, the response can be measured as in Eq. (2.8) that shows how much the liquid sloshes relative to the length of the tube. A higher maximum liquid response means larger liquid motion, which can affect the TLCD's performance and the design (e.g., risk of overflow, structural limits, etc.). The study (Gao *et al.*, 1997) reports maximum liquid responses in the range of 0.05 to 0.25, that would mean the liquid moves up to 5–25% of the total TLCD length. This is a key indicator when assessing whether the TLCD is functioning within safe and efficient bounds.

$$\text{Maximum liquid response} = \frac{\text{Maximum amplitude of oscillation of the liquid in the TLCD}}{\text{The total length of the TLCD}} \quad (\text{Eq. 2.7})$$

#### 2.3.4. Optimization of the TLCDs

TLCD into structural systems gives a significant potential for vibration mitigation, with performance influenced by design parameters, fluid properties, and structural interactions, as demonstrated by multiple studies.

Gao *et al.* (1997) observed that the optimum tuning ratio ( $\chi$ ) typically lies between 97.5% and 99.2%, increasing slightly with the structure's natural frequency. The optimum head loss coefficient ( $\delta$ ) was found to increase with the area ratio, and it decreases as the excitation intensity increased. The equivalent structural damping, a measure of the damper's effectiveness, improved significantly with the TLCD and remained relatively stable across different excitation intensities. Additionally, the maximum liquid response (Eq. 2.8) was proportional to the excitation intensity but reduced as the area ratio increased. Higher mass ratios improved both structural damping and reduced liquid response amplitudes. An increase in the horizontal and length ratio ( $\gamma$ ) enhances structural damping performance, although it may result in slightly larger liquid motion within the TLCD. Overall, the system exhibited behavior similar to linear systems, and optimal damping performance was achieved through careful tuning of the TLCD's frequency and head loss parameters. Wu *et al.* (2005) concluded that a uniform cross-section is consistently the most effective configuration for a given mass ratio

(Eq. 2.6) and length ratio (Eq. 2.7). This makes the design more straightforward and efficient for practical applications.

To further improve effectiveness, Gao *et al.* 1999; Yalla *et al.* 2000; Ahadi *et al.* 2012; Mohebbi *et al.* 2015 introduced Multiple Tuned Liquid Column Dampers (MTLCDs), where each TLCD is tuned with distinct dynamic parameters. They focused on optimization process in minimizing the maximum structural displacement. It was also detected that the total mass ratio of the MTLCDs significantly influences performance, higher mass ratios led to better vibration control. Furthermore, the response of the optimally designed MTLCDs varied with different seismic inputs, highlighting the importance of earthquake characteristics in determining their effectiveness. MTLCDs are more effective when there are unexpected deviations from optimal design parameters (such as changes in building stiffness, mass, or damping due to aging or construction variations). It requires lower optimal damping ratios, aligning with TLCD limitations. Their compact design allows flexible installation, even in tight spaces using nested configurations. These features make MTLCDs a versatile and effective passive control system for both SDOF and MDOF structures, especially under broadband or uncertain excitations.

However, Yalla *et al.* 2000, observed that increasing the number of dampers results in a flattening of the frequency response function, similar to the effect of increased damping in classical systems. However, beyond a certain number (e.g., 11 dampers), further increase in dampers produced diminishing returns. Whereas, Mohebbi *et al.* 2015 stated that MTLCDs and MTMDs show similar performance, but MTMDs slightly outperform MTLCDs under some real excitations.

Dziedziech *et al.* 2017, studied on the experimental identification of instantaneous vibration parameters in TLCDs. It was seen that the first mode exhibits quadratic damping behaviour, confirmed through analytical, numerical, and experimental analyses. The second mode reveals a more complex dynamic pattern, with natural frequency and damping ratio increasing as vibration amplitude decreases, suggesting strong displacement and velocity dependent nonlinearities. Overall, the study highlights the importance of capturing time-variant characteristics in TLCD dynamics and calls for future investigations into the higher modes and nonlinear behavior of such systems.

Colwell and Basu (2009) research on the MR (magnetorheological) fluids enhance damping passively, offering compact designs and resilience during power outages. Denser

fluids improve mass ratios, though added weight requires careful handling. Shah *et al.* (2023) investigates the optimal positioning of a TLCBD in a four-story structure using fluids with varying characteristics; water, sugar solution, and motor oil. The TLCBD was placed and tested at 2nd, 3rd, and 4th story levels. Ten cases were studied, including one uncontrolled and nine controlled cases. The results demonstrated that all controlled cases led to a reduction in structural vibrations, with the most notable performance observed when the TLCD was installed on the 4th floor. In that position, RMS acceleration was reduced by 56.54% (motor oil), 51.03% (sugar solution), and 54.60% (water). Overall, motor oil consistently outperformed the other fluids at all positions.

Di Matteo *et al.* (2015) proposed a novel mathematical model for the Tuned Liquid Column Damper (TLCD) using fractional calculus, aiming to more accurately capture the dynamic behavior of liquid motion within the damper. Traditional TLCD models often fall short in predicting experimental outcomes due to their inability to account for sloshing effects and deviations in natural frequency. By incorporating the first linear sloshing mode through an equivalent mechanical analogy and introducing a fractional derivative in the governing equation, the proposed model successfully modifies both the resonant frequency and damping characteristics of the system. From an experiment study, it was validated that this fractional model closely matches real liquid surface displacements, significantly outperforming the classical formulation. However, the model still relies on experimentally determined parameters and currently lacks a direct correlation between these parameters and the geometric properties of the TLCD, limiting its standalone predictive capability. Further research is needed to generalize this approach and enable its use as a virtual experiment or design tool.

Navdar *et al.* (2025) emphasized that drift sensitivity coefficients ( $\theta > 0.2$ ) necessitate P- $\Delta$  consideration in design, as lateral stiffness reductions amplify TLCD efficacy. Experimental and numerical methods showed aligned optimal lengths (192–195 cm), with P- $\Delta$  effects improving damping ratios by up to 3.6 times and reducing accelerations and displacements by 52% and 36%, respectively. It was seen that TLCDs coupled with P- $\Delta$  effects achieve up to 79% vibration reduction under seismic loads, validating their use in extreme conditions. Experimental-numerical alignment (e.g., 1.5% error in TLCD length) supports computational design methods.

Cao, 2025 did a comparison test between types of mass damper with the U- shaped TLCD (UTLCD or TLCD). It highlighted that, the peak dynamic magnification factor ( $DMF_{max}$ ) of

the structures with, UTLCD has the lowest value. It was also observed that an increase in mass ratio led to improved performance, indicating that the control efficiency of the device enhances as the damper’s weight relative to the structure increases performing better than conventional mass dampers, as shown in Figure 2.7. DMF is ratio of the steady-state response amplitude to the static response amplitude under harmonic loading. In this context, the dynamic response refers to the structural displacement due to oscillatory forces, while the static response represents the displacement caused by a constant static force of the same magnitude. Therefore, lower the value of  $DMF_{max}$  better the performance. However, the robustness of the structure is also analyzed by changing the stiffness and mass, TMD has the most robust characteristics and UTLCD shows least robustness but UTLCD gives better vibration reduction capacity in stable structure while in varying mass and stiffnesses due to change in water level, thermal expansion or structural modification TMD is a better option.

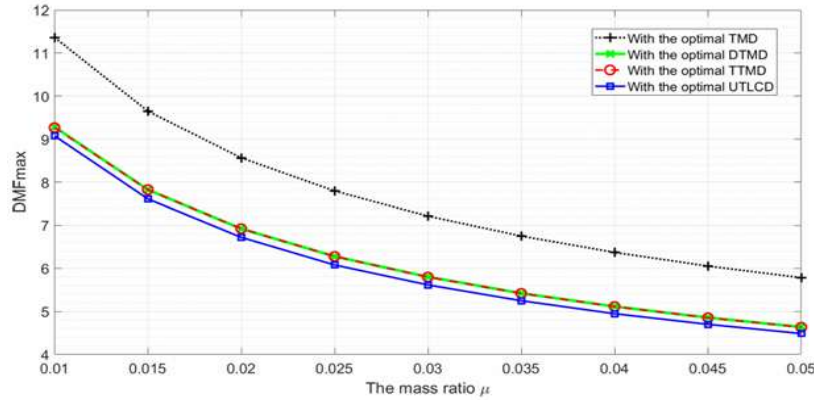


Figure 2.7: Pareto curves of the TMD, DTMD, TTMD, and UTLCD systems (Cao, 2025)

To assess damping sensitivity, the damping ratio for each device is varied within a range of -20% to +20%. Unlike TTMD and DTMD, the damping behavior of the UTLCD is non-linear, as its damping ratio is derived from the head loss coefficient rather than being constant. As observed in the Figure 2.8, UTLCD and DTMD has slight difference where UTLCD has the lowest damping ratio by only 1.4% and TTMD is the most sensitive device. The main reason for UTLCD as the lowest damping sensitive is due to the non-linear damping coefficient and the absolute moving velocity of the liquid column.

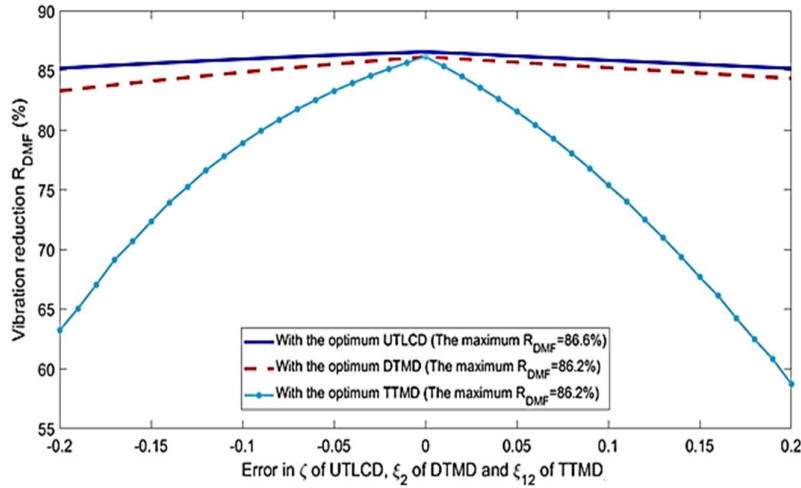


Figure 2.8: The sensitivity to the change in damping ratio of the UTLCD, of the DTMD and of the TTMD at  $\mu$  2%. (Cao, 2025)

Another comparison test was conducted by Kebeli *et al.*, 2024, TLD vs TLCD. They have considered 4 different water height of TLD and TLCD, as given in Figure 2.9. In Figure 2.10 (a) indicates that TLD perform better overall in reducing peak acceleration, peak displacement giving better damping ratio, especially at higher liquid heights (20 cm). However, TLCD of 5 cm model shows higher damping ratio than TLD 5 cm model, making TLCDs more effective in space-constrained applications. Hence, TLD system are generally more effective compared to TLCD specially when designed with higher liquid heights (Figure 2.10 (b)), but TLCD system can still have more advantages where space limitation exists and higher damping ratio is needed.

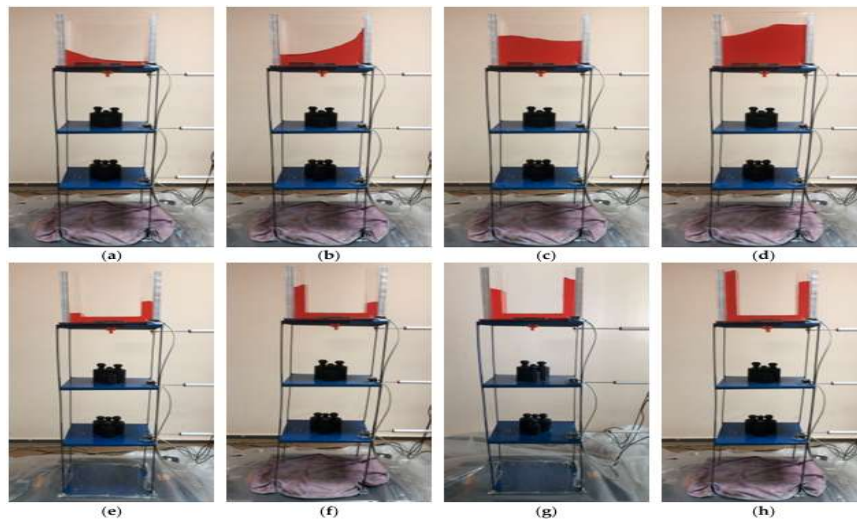


Figure 2.9: The experimental setup in mechanic laboratory: (a–d) with TLD 5, 10, 15 and 20 cm; (e–h) with TLCD 5, 10, 15 and 20 cm, respectively. (Kebeli *et al.*, 2024)

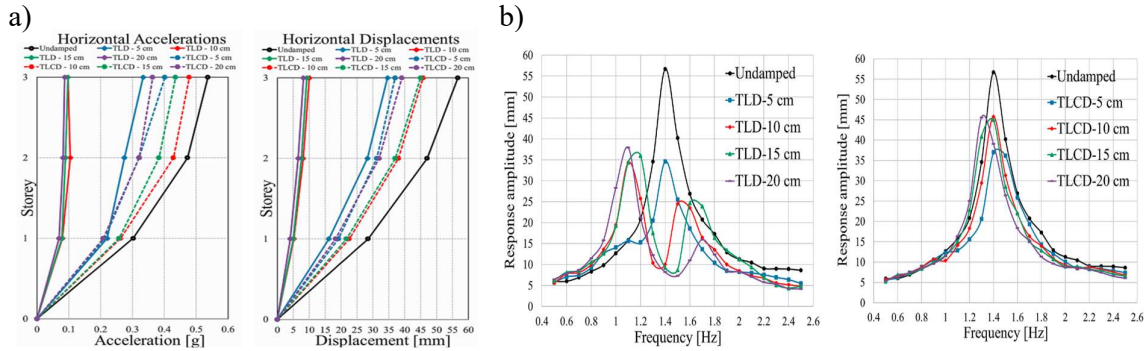


Figure 2.10: (a) acceleration and displacement values of each storey. (b) Experimental frequency–response curves for TLDs and TLCDs. (Kebeli *et al.* 2024)

The application of Tuned Liquid Column Dampers (TLCDs) for vibration mitigation in offshore wind turbines has also been explored, primarily due to their cost-effectiveness and adaptability to harsh marine environments. Han *et al.* (2025) research on TLCD for floating offshore wind turbines to get structural stability under stochastic marine environments. This model is primarily used for optimizing TLCD parameters to improve vibration control in floating wind turbines. TLCD effectively reduces vibration amplitudes at dominant frequencies, leading to lower fatigue loads. Mi-An Xue *et al.* (2024), stated that TLCDs are effective in reducing vibrations but may increase displacement due to liquid resonance at certain frequencies. However, they become highly effective at frequencies above 2.4 Hz. Also, the damping effect of TLCDs improves with increasing liquid depth ratio ( $D/L$ ), achieving up to 84.58% displacement reduction at  $D/L = 0.7$ .

Han *et al.* (2025) conducted a comparison experiment between TMD and TLCD were, TMD shows slightly better effective reduction than TLCD particularly at low wind speeds. A time series simulation was carried out on TMD and TLCD. TMD shows excessive displacement. The TMD reaches the maximum stop limit of 8 m, meaning it continuously hits the stop during operation. This repeated impact increases the risk of mechanical failure and structural damage to the damper system. TMD have mechanical limitations of wear and tear, simultaneously hitting the mechanism can damage over time. TLCDs on the other hand use liquid motion which makes them less prone to mechanical failure. They are also cheaper than TMD. Therefore, TLCDs are the better choice due to their low cost, ease of implementation, and robustness. Bigdeli and Kim, 2016 conducted an experimental test on passive control systems, such as TMD, TLD, and TLCD, are increasingly applied to reduce structural vibrations under dynamic loads. Experimental investigations show that while all three systems contribute significantly to damping, TMDs offer the highest damping performance, followed

by TLCs and then TLDs as shown in Figure. 2.11. A damping index was introduced to evaluate each system, revealing that this index decreases as the total mass of the controllers increases

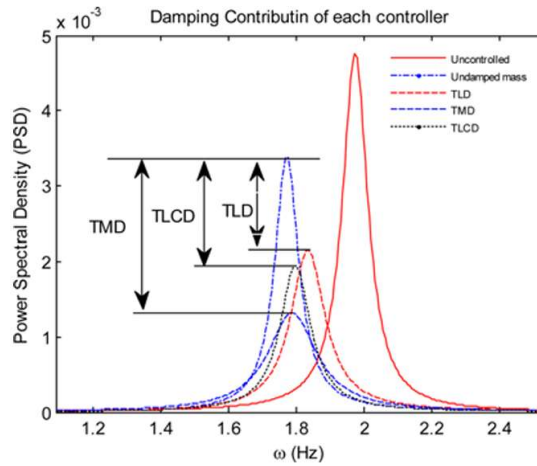


Figure 2.11: Comparison between analytical and numerical solutions. (Bigdeli and Kim, 2016)

### 2.3.5. Experimental Tests on TLCs

Researchers have employed various methods to evaluate the effectiveness of TLCs. Das *et al.* (2025a) investigated the influence of liquid sloshing in a TLC using a finite element model. A single-degree-of-freedom structure equipped with a TLC was analyzed under both far-field and near-field ground motions. The liquid within the TLC was assumed to be incompressible, inviscid, and irrotational, with sloshing behavior considered linear or weakly nonlinear under forced vibration. Two sets of ground motions are considered, one set of far-field and other having near-field records which are collected from FEMA P-695. de Oliveira Silva *et al.* (2025) introduces Singular Spectrum Analysis (SSA) to study and optimize vibration control in TLC systems, conducting experiments on a sliding vertical structure with a TLC and using R programming and FFT for analysis. Mendes *et al.* (2023) uses Newmark’s method and DynaPy software to analyze TLC performance. Figure 2.12 illustrate the comparison between the analytical and numerical displacement solution.

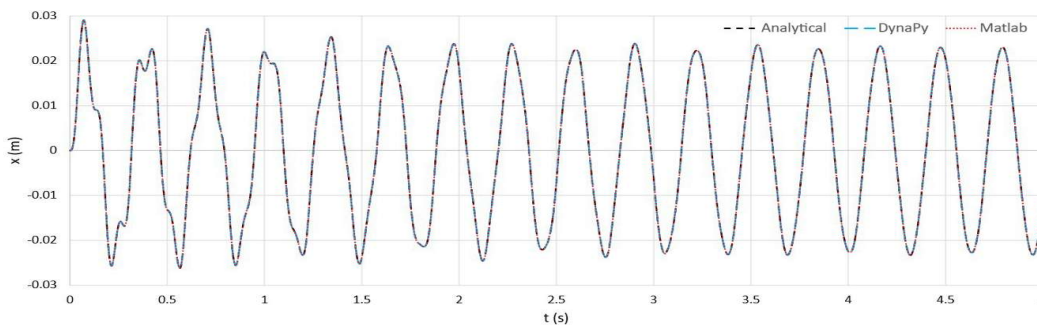


Figure 2.12: Comparison between analytical and numerical solutions. (Mendes *et al.* 2023)

To understand how the parameters influence the performance of the TLCD, it has considered a varied damping ratios from 0.3 to 0.12 with each combination of aspect ratio, mass ratio and tuning ratio, determining the optimal damping ratio. It was observed that an increase in the aspect ratio leads to a reduction in the response ratio, indicating that the TLCD becomes more effective in suppressing structural vibrations. Increasing the mass ratio reduces vibrations slightly but has a less significant impact compared to the tuning ratio. Navdar *et al.* (2025) conducted both numerical and experimental investigations on the design of a TLCD system for a slender single-degree-of-freedom (SDOF) structure, considering second-order (P- $\Delta$ ) effects. Slender structures are particularly susceptible to these effects. Following seismic events, such structures often exhibit a negative slope in the lateral load–displacement curve, indicating a reduction in stiffness and an increase in the natural period of the structure.

Recent research has also begun to explore the application and advantages of TLCDs in mitigating motion in offshore floating structures. Wang *et al.* (2025) investigated the use of Liquid Column Vibration Absorbers (LCVAs), a variation of conventional TLCDs. Unlike traditional TLCDs, LCVAs permit different cross-sectional areas in the vertical and horizontal columns, offering greater flexibility in design and adaptation to varying structural requirements. By incorporating pitch into the analysis, the researchers were able to more accurately simulate the dynamic behavior of floating platforms, such as floating breakwaters, under environmental loads. Their work highlights the potential of these passive systems in improving the dynamic performance of floating platforms under various wave conditions. Building on this, Han *et al.* (2025) focused on optimizing TLCDs for specific offshore applications, such as floating wind turbines and large floating platforms. Their research emphasized the importance of tuning parameters and design modifications to enhance the efficiency of TLCDs in diverse environmental settings. Complementing these approaches, Mi-An Xue *et al.* (2024) investigated the integration of TLCDs with other motion control systems, including tuned mass dampers (TMDs) and semi-active control strategies. Their study addressed both the technical challenges and practical considerations of implementing hybrid stabilization systems in real-world offshore structures. Collectively, these works underscore the evolving role of TLCDs and their hybrid variants in advancing the stability and reliability of offshore floating systems.

Comparison with different dampers is also studied such as by Cao (2025), developed three new passive dampers an upgraded tuned liquid column damper (UTLCD), tuned two-mass damper (TTMD) and double-tuned mass damper (DTMD). UTLCD model consist of an

undamped TMD and a smaller TLCD fixed on top of the TMD, TTMD is made up of two parallel undamped TMDs linked to a dashpot, and DTMD consist of two TMDs are placed on top of each other.

### ***2.3.6. Efficiency of the TLCDs in vibration Control***

Das *et al.* (2025a) observed that near field ground motions produced higher hydrodynamic forces than far field motions. It was observed that the sloshing effect significantly influences the RMS displacement values, with maximum reductions of 5.07% under near-field ground motions and 2.35% under far-field conditions. It was also observed that with increase in aptitude, sloshing also increases due to non-linear damping and fluid motion. TLCD perform best when the excitation frequency matches the structural frequency. In the study by Navdar *et al.* (2025), four real earthquake ground motions were selected from the PEER database to investigate the actual impact of TLCDs on the dynamic behavior of structures. The selection included two near-field and two far-field ground motions. To ensure that the test structure remained within the elastic range during analysis, all ground motion records were scaled by a factor of 0.10 (i.e., acceleration divided by gravitational acceleration,  $g$ ). From this experiment, the far-field earthquake showed higher vibration mitigation performance than near-field earthquakes. Using TLCD reduces the structural response more effectively in far-field earthquakes, and an equivalent linear model shows better results in near-field earthquakes. The study found that the longer the structural time period, the higher the  $P-\Delta$  effect and the reduced TLCD performance due to misalignment from the optimum tuning ratio. Additionally, the performance of the TLCD was found to decrease by approximately 5% to 35% as the drift sensitivity coefficient ( $\theta$ ) increased from 0.04 to 0.41. This indicates that neglecting second-order effects ( $P-\Delta$  effects) in TLCD design can lead to a substantial reduction in vibration mitigation effectiveness, particularly in flexible structures. Therefore, it is essential to consider  $P-\Delta$  effects during the tuning and design of the TLCD system to ensure optimal performance. Shah and Usman (2022) Near the resonance, RMS acceleration reduces to 85% at 1<sup>st</sup> storey. When the frequency is below 0.9 Hz TLCD was not effective however frequency increases above 1.1 Hz the TLCD performances slightly drops. This is because TLCD is tuned to resonate only within arrow frequency range. It was observed that TLCD works best at 1.30 Hz (resonance), reducing it to less than 0.05  $g$  acceleration (94% in peak acceleration). The reduction is also seen in the seismic loading. In Power spectrum density (PSD) analysis also confirms the damping effect of TLCD by showing suppressed frequency peaks resulting in decrease in vibration energy due to the damping.

### ***2.3.7. Limitations of the TLCDs***

The Tuned Liquid Column Damper (TLCD) is a widely adopted and reliable device for mitigating wind-induced vibrations in buildings, owing to its high volumetric efficiency, ease of tuning, effective damping mechanism, low installation and maintenance costs, and the added advantage of serving as an emergency water source for firefighting. Several configurational variants, such as bi-directional TLCDs, liquid column vibration absorbers (LCVA), and TLCDs with air springs have also been implemented in real structures to enhance occupant comfort under wind loading. Despite these successful applications, TLCD systems present several limitations.

#### *a) Lack of Full-Scale Experimental Validation for New Variants:*

While several new configurations of TLCDs, such as toroidal TLCD, omnidirectional TLCD, tuned liquid column ball damper, tuned liquid multi-column damper, circular TLCD, compliant TLCD, and TLCD-inerter have shown promise in theoretical and experimental studies, full-scale experimental investigations and real-world implementations of these systems are still lacking.

#### *b) Limited to Long-Period Structures:*

TLCDs have predominantly been installed in long-period (typically taller) structures. Although research suggests that configurations like compliant TLCDs and air-spring-assisted TLCDs can effectively control vibrations in short-period (shorter) structures, they have not yet been implemented in real-life buildings.

#### *c) Single-Mode Focus:*

Most existing installations of TLCDs are optimized to control the first (dominant) mode of vibration. However, in practical applications, especially in irregular or complex structures, multi-modal vibration control is necessary but underexplored with TLCDs.

#### *d) Lack of Seismic and Multi-Hazard Applications:*

Current TLCD applications are primarily focused on mitigating wind-induced vibrations. Their potential for seismic vibration control remains unexplored, and their behavior under multi-hazard scenarios (e.g., wind and earthquake combined) has not been addressed in existing studies or real-world installations.

### 2.3.8. Hybrid TLCD

Hybrids are the combination of different control parameters within one system to improve vibration mitigation. Rather than relying on one type of damper or isolation strategy, hybrid systems combine the advantages of multiple technologies to achieve better performance across a broader range of dynamic excitations. This section will be discussing on the hybrids with TLCD.

Adam *et al.* 2017; Furtmüller *et al.* 2019, conducted an experiment on a hybrid control that consists of a base-isolation system and a TLCD to reduce structural vibrations due to seismic forces. The experiment used a small-scale three-story shear frame model as shown in Figure 2.13. For investigating the performance of TLCDs with various frequency tuning ratios, the base-isolated structure was equipped. The dynamic characteristics of the frame, the base-isolation system, and the TLCDs were assessed through displacement and acceleration measurements.

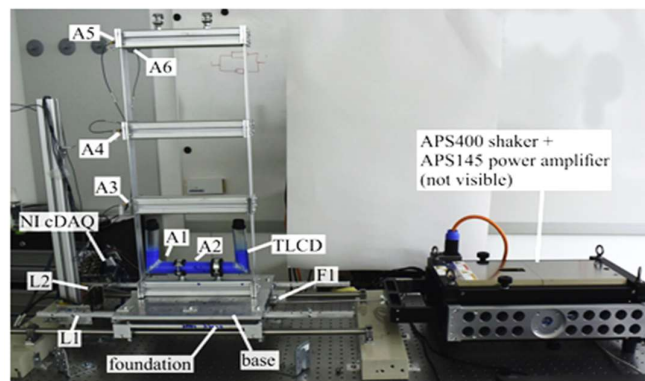


Figure 2.13: Test set up with sensor locations A1 to A6. (Furtmüller *et al.*, 2019)

The experimental results shows that the well-tuned hybrid control system (base-isolation + TLCD) effectively reduced both base displacements and story accelerations. The results also revealed that optimal vibration control is achieved when the TLCD is tuned to the natural frequency of the base-isolation system.

To leverage the strengths of TMD and TLCD devices while mitigating their respective limitations, Di Matteo *et al.* 2017 proposes a novel passive control system called the Combined Tuned Damper (CTD), which has the TMD and TLCD into a single hybrid device. The governing equations of motion are formulated for a general multi-degree-of-freedom system, and an analytical investigation is conducted to evaluate the control performance of the CTD. Various tests were conducted including sinusoidal base excitations, to evaluate the acceleration

response of a multi-story model equipped with different damper configurations (TMD, TLCD, and CTD). The CTD effectively combines the high performance of the TMD with the economic advantages of the TLCD. It provides comparable vibration mitigation to that of a standalone TMD. The experimental and numerical results show excellent agreement, confirming the validity of the proposed mathematical model. The CTD shows promise for full-scale structural applications and may serve as a viable alternative to conventional damping devices.

However, the system is sensitive to changes in excitation frequency, and precise tuning of both the mass and liquid components is essential. Additionally, it may require more space and add significant weight to the structure. The nonlinear behavior of the liquid column under large excitations can also reduce predictability and complicate analysis.

Sarkar and Gudmestad 2013, introduced a Pendulum Liquid Column Damper (PLCD), a hybrid passive control system that integrates the working principles of both a TMD and TLCD (Figure 2.14). It was developed to suppress structural vibrations induced by dynamic loads such as wind or earthquakes, combining the inertial effects of a pendulum-type mass with the damping effects of liquid oscillations through an orifice.

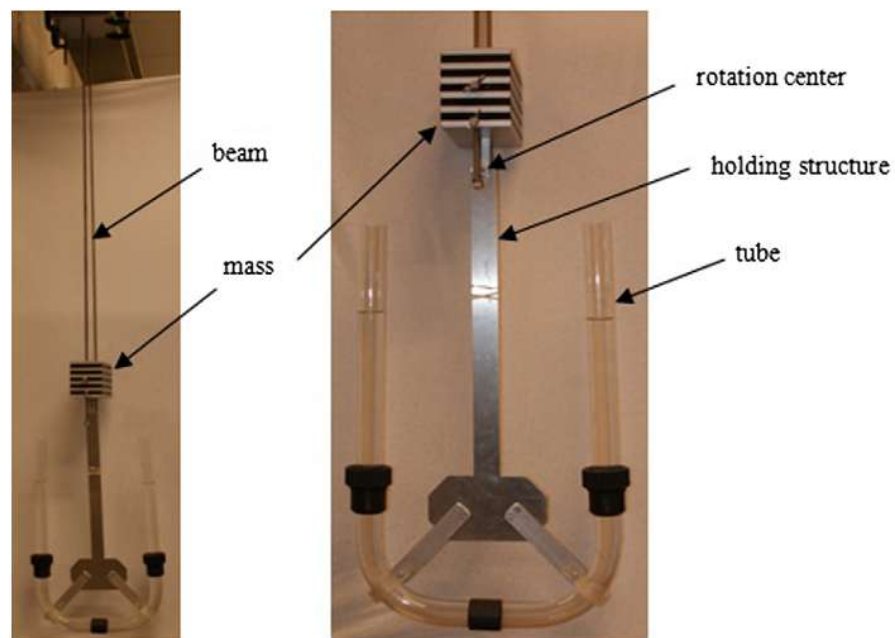


Figure 2.14: Fabricated model of PLCD with the primary structure.  
(Sarkar and Gudmestad, 2013)

This unique configuration allows for efficient energy dissipation and structural response control. The study focused on formulating a mathematical model for a two-dimensional case using Lagrange's equations and validated it experimentally using a cantilever beam setup.

While the experimental results confirmed the effectiveness of the PLCD in reducing vibrations, especially when the orifice opening was optimized, several limitations remain. The system introduces added complexity in analysis due to extra degrees of freedom and geometric nonlinearity from the pendulum motion. Moreover, the study does not provide optimized design parameters or comparative analysis with other damping systems, leaving its practical advantages yet to be fully established. Nonetheless, the PLCD shows potential for applications in slender structures like chimneys or offshore wind turbines, where compact and efficient damping solutions are required. Similar research was carried out by Furtmüller *et al.* 2022 on Pendulum Tuned Liquid Damper (PTLD) to control low-frequency vibrations in pendulum-type structures, like ropeway cabins. Their study involved both numerical modeling and experimental validation, highlighting the significance of damper placement and the need to account for nonlinear fluid damping, especially under shallow water conditions. Unlike the PLCD, their approach used a floating roof to manage wave breaking, and proposed a quadratic damping model to simulate the observed nonlinear behavior accurately.

#### 2.4. Tuned Liquid Column Ball Damper (TLCBD)

TLCBD consists of a rolling ball placed inside the TLCBD on the horizontal section which acts as a moving orifice (Figure 2.14). Due to the presence of ball, energy dissipation is improved as it causes resistance to flow, friction between the fluid and the ball kinetic energy of the rolling ball. It was first introduced by Al-Saif *et al.* in 2011.

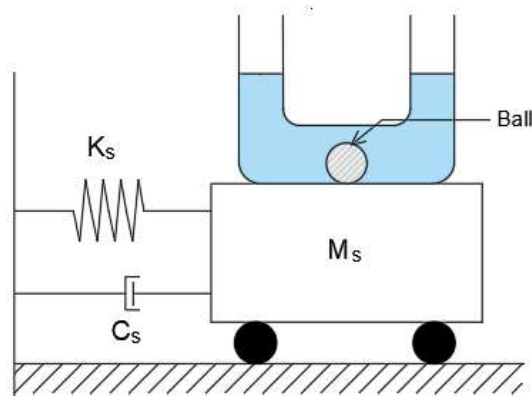


Figure 2.15: Tuned Liquid Column Ball Damper (TLCBD)

Gur *et al.* (2015) proved that TLCBD have significantly superior performance, reducing the structural response by up to 50% compared to TLCD. Moreover, TLCBD achieves this while requiring less liquid displacement (approximately 60%) of the liquid displacement in TLCD indicating more efficient energy dissipation. Although the TLCBD introduces a new

element, the ball, which exhibits large displacements at lower tuning ratios, this issue diminishes near the optimal operating point. Under changes in mass ratio, TLCBD shows adaptable optimal tuning ratios, while TLCBD's remain relatively fixed. This flexibility gives TLCBD a practical advantage, as it can deliver equal or better performance with lower liquid mass. When structural flexibility increases, TLCBD becomes even more effective, although ball displacement also increases and may limit use in highly flexible structures.

In contrast, TLCBD performance improves primarily through longer liquid columns, while TLCBD maintains strong efficiency even in more compact designs. For structures with low inherent damping, TLCBD is especially effective, and the ball displacement reduces, making it well-suited for lightly damped buildings. Importantly, the optimal parameters for both dampers remain consistent across various earthquake intensities, but the TLCBD's performance improves with stronger seismic forces due to enhanced damping behaviour.

The Tuned Liquid Column Ball Damper (Al-Saif *et al.* 2011) is an improvement upon traditional TLCBDs by replacing the orifice with a steel ball, resulting in a 67% increase in vibration suppression under harmonic excitations and the optimal diameter of ball ratio was 0.8 of the horizontal section height. Pal *et al.* (2020) investigated the optimized tuning ratio with mass ratio, and it was observed that as the mass ratio increases, the tuning ratio also changes significantly when the displacement is restricted. Higher constraints (lower allowable displacement) make optimization more rigid, leading to larger variations in tuning ratio as shown in Figure 2.16(a).

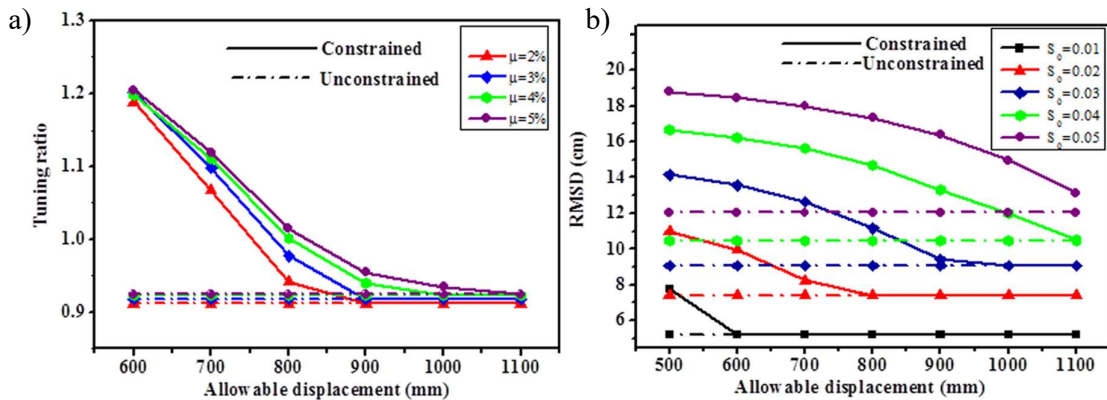


Figure 2.16: (a) The variation of optimized tuning ratio for different mass ratios with varying allowable displacement, (b) The RMSD with varying allowable displacement for different seismic excitation ( $S_o$ ). (Pal *et al.* 2020)

Also, the higher mass ratios cause more overlapping RMSD values at lower allowable displacements. Further enhancements with constrained liquid movement in the vertical column,

optimizing TLCBD performance under seismic conditions to manage excessive displacement and keeping system to move only upto 1100mm. When the allowable displacement is small, the structure experiences higher vibration responses. As allowable displacement increases, the RMSD decreases, implies better vibration mitigation. It was also seen that higher damping ratio leads to less liquid displacement which means the TLCBD can work effectively with less fluid movement. While comparing different level of seismic excitation, it was seen that the stronger earthquakes cause greater structural displacement. At higher seismic intensities, the constrained and unconstrained cases overlap (less effective), as shown in Figure 2.16(b). Proper liquid movement constraints are essential for designing TLCBDs for high-intensity earthquakes.

Tanveer *et al.* (2019) conducted a comparative study between Tuned Liquid Column Dampers (TLCD) and Tuned Liquid Column Ball Dampers (TLCBD) on a four-storey steel frame structure. The analysis considered varying mass ratios ranging from 2% to 5%, and excitation frequency ratios between 0.5 and 1.2 were applied to evaluate performance. The length ratio and tuning ratio were taken as 0.7 and 0.97, respectively, while the ball-to-tube diameter ratio for the TLCBD was set at 0.8. As the excitation frequency ratio decreased from 0.9 to 0.7, both TLCD and TLCBD demonstrated a reduction in vibration response; however, TLCD showed superior performance under these conditions. TLCBD shows better performance in the resonance region also mass ratio is dependent TLCD and also performed better compared to TLCD as observed in Figure 2.17.

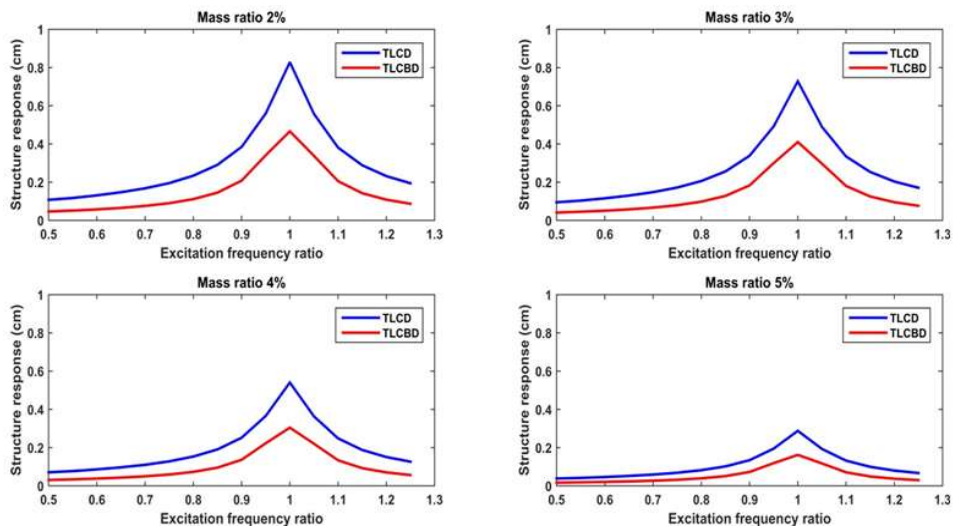


Figure 2.17: Variation of displacement of structure with various excitation frequency ratios and mass ratios (Tanveer *et al.* 2019)

To design TLCBD of MDOF, Al-Saif *et al.* (2011); Chatterjee and Chakraborty (2014); Gur and Mishra (2015) steps for designing SDOF-TLCBD was adopted. Experimental results revealed that the TLCBD-controlled structure exhibited improved RMS and peak acceleration responses compared to the TLCD-controlled structure. However, in some cases, the peak acceleration response of the TLCBD was observed to be higher than that of the TLCD.

Three types of harmonic and sine sweep were considered and seismic loading was also applied which are Northridge and Kobe. The Northridge earthquake responses show better performance especially in TLCBD as compared Kobe earthquake. The response reduction increases from 1<sup>st</sup> storey to top storey in sine sweep, Northridge, and Kobe excitation but it doesn't show the same under harmonic loading as each storey had different frequency response. The best performance was observed on the top floor as shown in Figure 2.18 and both the TLCBD and TLCD shows similar trend of reduction. The effectiveness of TLCBD and TLCD may reduce on strong excitation but TLCBD was more effective under low amplitude seismic excitations and also performed well under harmonic loading.

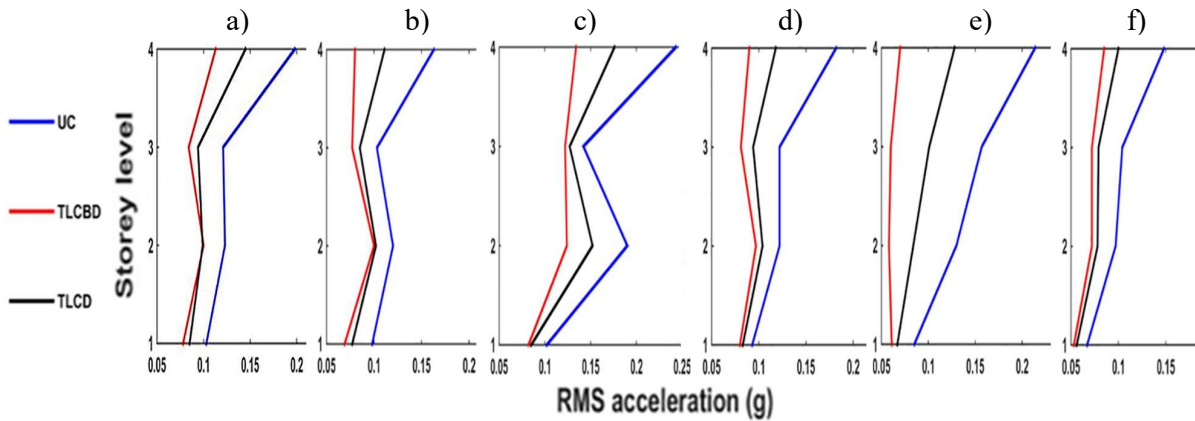


Figure 2.18: RMS acceleration responses comparison of TLCBD, TLCD and Uncontrolled structure: (a) 0.5Hz; (b) 1Hz; (c) 1.5Hz; (d) Sine sweep; (e) Northridge; and (f) Kobe. (Tanveer *et al.*, 2019)

Later on, Tanveer *et al.* (2020) conducted a same experiment but on various liquid and ball which are sugar solution, water and oil and for ball, lead, steel and aluminum balls are used. The result shows maximum reduction in TLCD was observed in 1Hz for harmonic loadings and the Northridge earthquake produces highest reduction in response compared to Kobe earthquake. It was observed that among the test the sugar solution gives better response reduction than water and oil. For the balls, leads outperforms the steel and aluminum in terms of vibration control. This confirmed that TLCBD is an effective passive vibration control device, particularly for seismic excitations, and highlighted the importance of selecting the right liquid and ball densities for optimal damping performance. Das 2022 also conducted a

comparative study on TLCD with submerged cylinder and traditional TLCDs. The results suggested that the cylindrical motion within the liquid helps improve the damper's overall performance, offering a promising approach for reducing structural vibrations in high-rise buildings and other flexible structures. It reduced liquid displacement with larger cylinder diameters, making the system suitable for high-amplitude vibrations, and sensitivity to earthquake spectra.

Pandey and Mishra (2018) proposed a hybrid system combining a Tuned Liquid Column Ball Damper (TLCBD) with a Circular Liquid Column Ball Damper (CLCBD), as illustrated in Figure 2.19, to control torsionally coupled vibrations in buildings subjected to wind excitations. Steel balls were placed at the midpoint of the liquid column to enhance energy dissipation. This study demonstrated the superior control efficiency and achieves a significant reduction in liquid column displacement compared to conventional TLCDs. These analytical findings are also supported by results from shake table experiments, further confirming the effectiveness of the proposed approach.

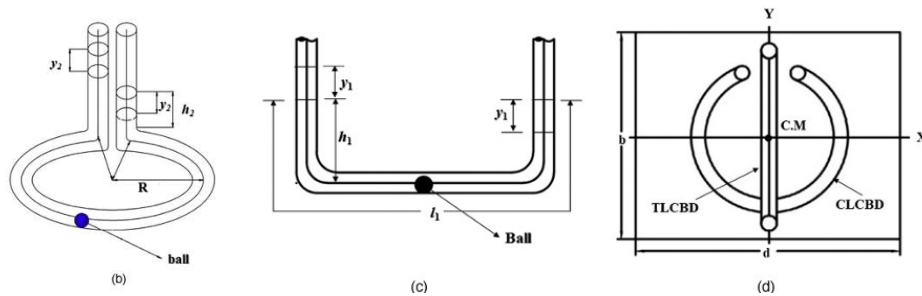


Figure 2.19: Torsionally coupled building in plan to the (a) CLCBD (b) TLCBD and (c) the configuration of the combined CLCBD–TLCBD system on the top of the building. (Pandey and Mishra 2018)

Shah *et al.* (2021) developed a hybrid system combining features of a tuned mass damper and a tuned liquid column damper, introducing two novel devices: the Tuned Liquid Column Ball Spring Sliding Damper (TLCBSSD) and the Tuned Liquid Column Ball Spring Rolling Damper (TLCBSRD). In the TLCBSSD, a spring is welded to the surface of the ball and attached to the column wall, enabling the ball to slide within the TLCD, as illustrated in Figure 2.20(a). In the TLCBSRD, the ball is welded to the spring in such a way that it can both translate and rotate inside the TLCD, as shown in Figure 2.20(b).

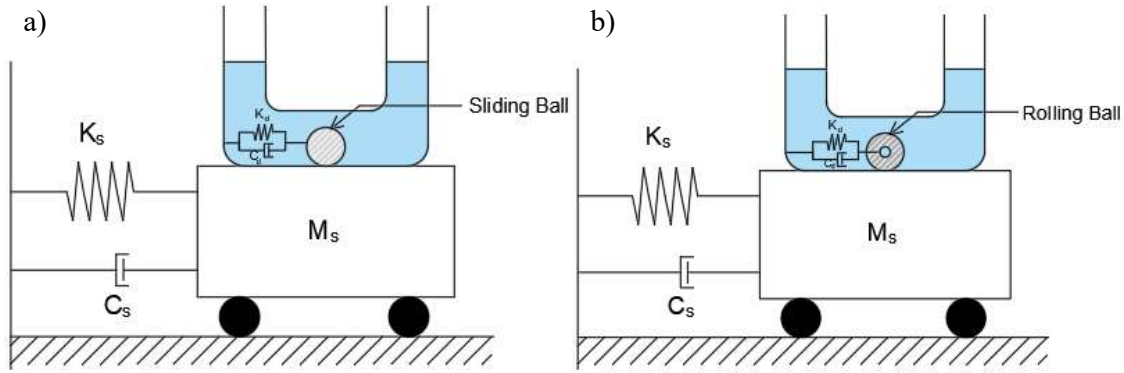


Figure 2.20: Structure with (a) tuned liquid column ball spring sliding damper (TLCBSSD), (b) Tuned liquid column ball spring rolling damper (TLCBSRD). (Shah *et al.*, 2021)

Finally, a TLCD incorporating a freely moving solid ball, referred to as the Tuned Liquid Column Ball Damper (TLCBD) was developed, where the ball functions as a moving orifice. This configuration is illustrated in Figure 2.14. Taking optimal tuning ratio from TLCBD as 0.98, TLCBSSD performed best when it is equal to 1.4 and TLCBSRD at 1.6. The length ratio of 0.8 provides best performance at tuning frequency 1.02 and maximum response reduction of 58.68% were achieved. After considering all the parameters and the performance, the design specifications for the TLCBSSD and TLCBSRD systems are as follows: the tuning frequency of the liquid column is set at 0.98, the length ratio is 0.8, the spring damping ratio is 0.1, the optimum tuning frequency for the spring-ball system is 1.6, and the density of the ball is 8050 kg/m<sup>3</sup>. It was observed that TLCBSSD reduces by 30% and TLCBSRD reduces by 32% under harmonic loading and in seismic loading of 1940 EI Centro earthquake TLCBSSD reduces by 29% and TLCBSRD by 28% and TLCBD by only 12%. Therefore, the newly proposed TLCBSSD and TLCBSRD outperform the TLCBD.

Shah *et al.* (2023a) later on conducted an experiment to study the effect of TLCBSSD, TLCBSRD and TLCBD on a 4-storey steel frame structure. The frequency responses of the dampers were analyzed in which the TLCBSSD (Figure 2.21(a)) and TLCBSRD (Figure 2.21(b)) perform better than TLCBD. TLCBSRD performs slightly better than TLCBSSD. This may be due to the rolling mechanism which was absent in TLCBSSD.

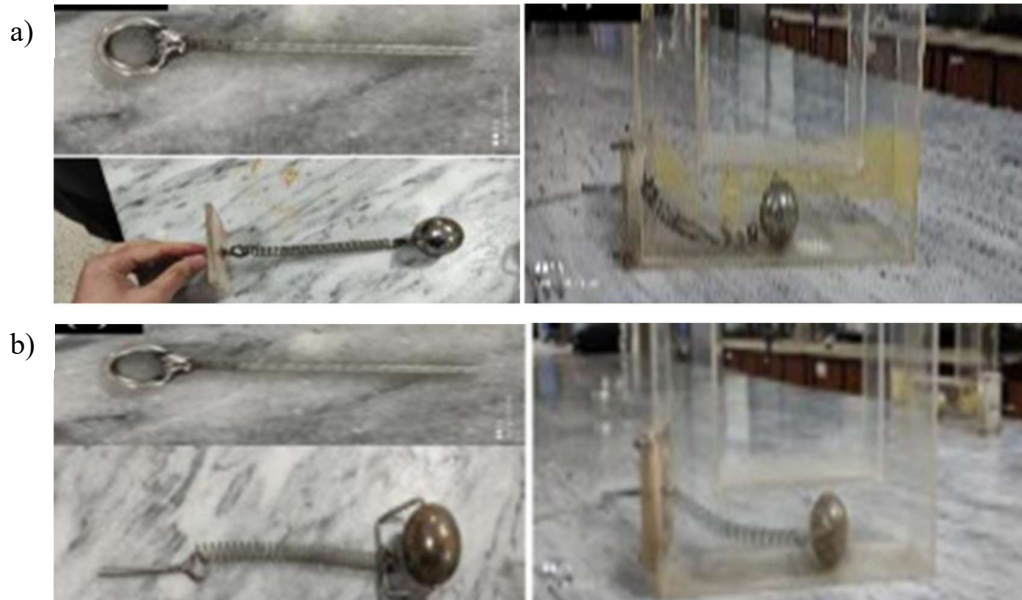


Figure 2.21: Fabrication representation of (a) TLCBSSD and (b) TLCBSRD (Shah *et al.* 2023a)

The TLCSSD, TLCSR and TLCBD were experimented on a 4-story building. Under harmonic loading the three mechanism and uncontrolled system were compared were TLCSSD and TLCSR perform almost similar beyond resonance but in the resonance TLCSR perform slightly better as shown in Figure 2.22. This may be due to the addition of spring mechanism which was absent in the TLCBD. Even in seismic loading TLCSSD and TLCSR perform better than TLCBD. In Figure 2.23, it was seen that TLCBSSD and TLCBSRD damper performed well compared to TLCBD for inter-story drift as well as in case of displacement and acceleration the performance of TLCBD, TLCBSSD, and TLCBSRD have a similar trend in the reduction.

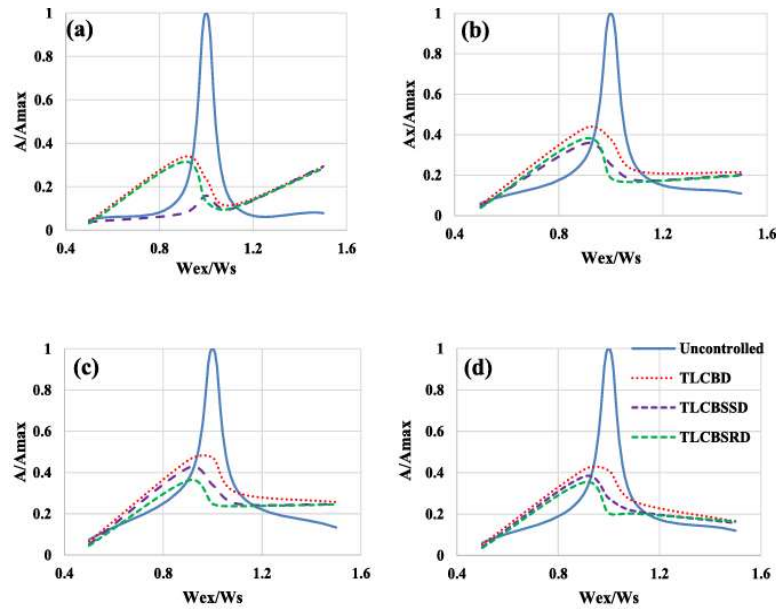


Figure 2.22: Normalized frequency responses of structure with TLCBD, with TLCBSSD, and with TLCBSRD compared to the uncontrolled structure. (a) The first story (b) Second story, (c) Third story, and (d) Fourth story. (Shah *et al.* 2023a)

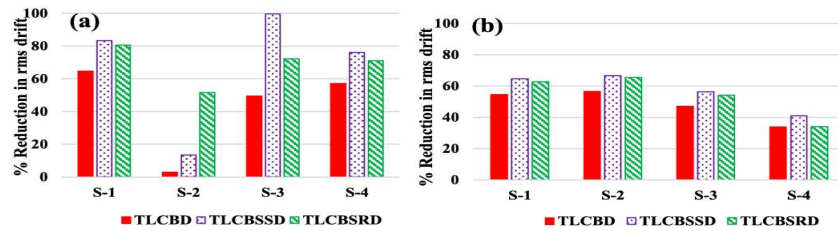


Figure 2.23: Percentage (%) reduction in the RMS inter-story drift of TLCBD, TLCBSSD, and TLCBSRD against uncontrolled structure under (a) Resonant loading and (b) 1940 EI Centro earthquake loading. (Shah *et al.* 2023a)

Finally, it was stated that the purposed mechanisms are better dampers than traditional TLCBDs. However, further studies are needed to better understand the characteristics and underlying factors that influence the performance of the damper. A study on Multiple Tuned Liquid Column Ball Dampers (MTLCBDs) is also carried out by Veisi and Toopchi-Nezhad (2022). As TLCBD system can require large dimension when applying to large structure and can sometimes be costly, to address this issue MTLCBDs are introduced, Figure 2.24.

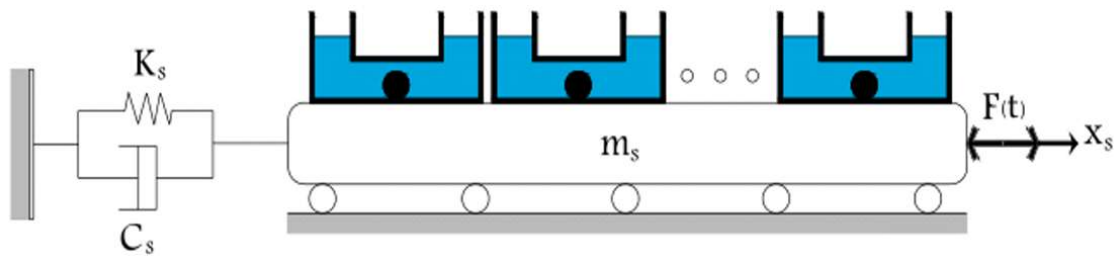


Figure 2.24: A structure equipped with MTLCBDs. (Veisi and Toopchi-Nezhad 2022)

Parametric study was carried out, it was seen that a system with  $n$  identical dampers, each having the same mass and length ratios that performs equivalently to a single TLCBD with a total mass ratio of  $\mu = n\mu_i$  and the same length ratio  $\gamma = \gamma_i$ . The response mitigation efficiency of MTLCBDs can be enhanced by increasing the number of dampers, the mass ratio, or the length ratio. MTLCBDs offer a space- and cost-effective alternative to single TLCBDs and are especially beneficial for mitigating higher vibration modes in tall buildings under wind loads.

## **2.5. Compliant Tuned Liquid Column Dampers (CTLCD)**

### ***2.5.1. Compliant Mechanisms: The Beginning***

Tuned Liquid Dampers (TLDs) are typically effective only for flexible (long-period) structures. This is because the TLD is inherently a long-period device, which tuned to work best with structures that vibrate slowly. The natural frequency of an TLD is determined by the length of its liquid column and is inversely proportional to the square root of that length. So, to match the high frequency of a stiff (short-period) structure, a need for an impractically short liquid column, which isn't feasible in practice.

Over the years several past studies (Balendra *et al.*, 1995; Tanveer *et al.*, 2019; Pal *et al.*, 2020; Das *et al.*, 2025a) as discussed in the previous section, have emphasized the effectiveness of tuned liquid devices in mitigating seismic vibrations in buildings and structures. These studies conclude that the control efficiency of such devices is highly dependent on their proper tuning with the dynamic characteristics of the structural system. However, it was observed that the tuning can be further improved by introducing some compliant mechanism to the TLCBD – structure system for application to short-period structures.

A compliant mechanism is a structure that have motion and force transmission through flexible system. To control the nonlinear behavior of structures during earthquakes using a damper system that combines a TLD with a spring connection to the structure. The nonlinear structural response is modeled using a Single-Degree-of-Freedom (SDOF) system with bilinear hysteresis to capture inelastic behavior. To simplify analysis and control, the nonlinear system is approximated by an equivalent linear system through a temporal averaging technique, and the resulting linearized frequency is used to tune the damper. The use of a spring-connected TLD eliminates the need to directly match the damper's frequency to that of the structure, which is particularly beneficial when the structural frequency is high or varies during an earthquake. This compliant mechanism gives an effective damping on the short period

structure. As mention in above short period structure has higher natural time period, leads to unrealistic tuning.

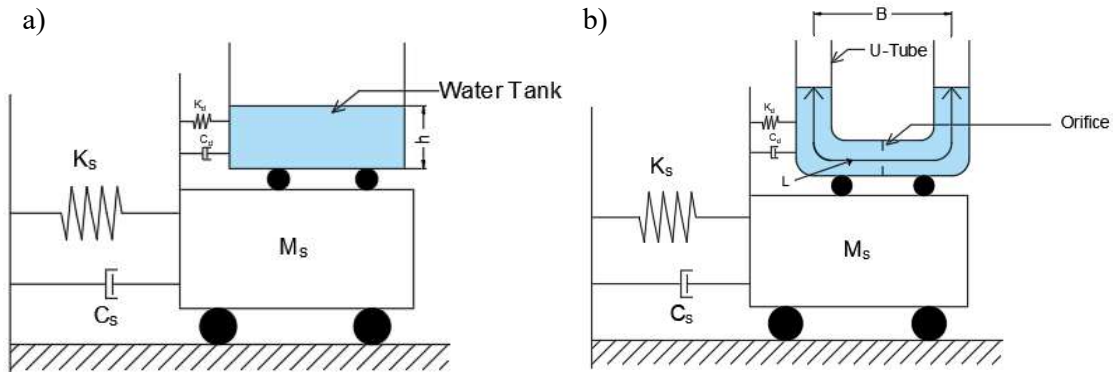


Figure 2.25: Compliant a) Tuned Liquid Damper and b) Tuned Liquid Column Damper.

As observed in the previous studies all the dampers are fixed on top of the structure. The flexibility allows adaptive tuning of the natural frequency or adds damping through structural deformation. In the Figure 2.25, indicates the compliant mechanism of the TLD and TLCD. The CTLDs and CTLCDs, moves out-of-phase with the liquid contributing in dissipation of energy. Ghosh and Basu (2004) demonstrated that CTLCDs are effective in controlling vibrations in lightly damped, stiff structures, though their efficiency decreases as inherent structural damping increases which comes under short period structures. The range of the time period for short-period structures typically falls between 0.1 seconds and 0.5 seconds. These structures are generally stiff and have higher natural frequencies, meaning they respond quickly to dynamic loads such as seismic forces. The natural frequency is directly proportional to the square root of stiffness and inversely proportional to the square root of mass,  $f \propto (k/m)^{(1/2)}$ . So, an increase in stiffness or a decrease in mass leads to a higher natural frequency. A short-period structure reaches its peak acceleration and displacement values relatively quickly during an earthquake. Because short-period structures respond quickly, any damping system needs to be able to act rapidly to be effective. TLCDs, when properly tuned, can provide this rapid damping.

Ghosh and Basu (2004) applied a spring-connected Liquid Column Damper (TLCD) for short-period structures. LCD was highly effective on lightly damped (eg. tall or stiff structure that have little energy dissipation). When the structural damping increases from 0 to 20%, the additional damping from LCD declines. This highlights the LCD's potential as a passive control device, particularly for stiff or moderately stiff buildings with low damping.

Afterwards, Ghosh and Basu (2008) modelled a Single-Degree-of-Freedom (SDOF) systems with bilinear hysteresis, a way to represent nonlinear, inelastic behaviour during strong shaking. To simplify analysis and design, a differential model of the hysteresis loop is used, and the system is then linearized through an equivalent linearization procedure. This process gives the natural frequency and damping ratio of a hypothetical linear version of the nonlinear system. These values are then used to design the spring-connected LCD.

Bhattacharyya *et al.* (2017b) validated and optimized the performance of a Compliant Liquid Column Damper through experimental testing, focusing on refining its tuning and damping mechanisms for effective seismic vibration control. When CLCD is attached to the structure applying harmonic excitation on the base of the structure. Two peaks were observed one near the structural natural frequency and other near the liquid column frequency in dictation effective coupling between the structure and the CLCD. The CLCD effectively reduced the structural acceleration response, particularly at resonance, showing strong agreement between experimental results and theoretical simulations. When applied to a single-degree-of-freedom (SDOF) structure, the CLCD achieved up to a 61.1% reduction in acceleration at resonance.

A short-period stiff structure with mass ( $M_s$ ) with an overhead mounted sliding Tuned Liquid Column Damper (STLCD) was investigated theoretically and experimentally by Masnata *et al.*, 2024 as shown in Figure 2.26 and a spring- dashpot is involved as a sliding mechanism for the STLCD. The structural responses were studied under harmonic excitation.

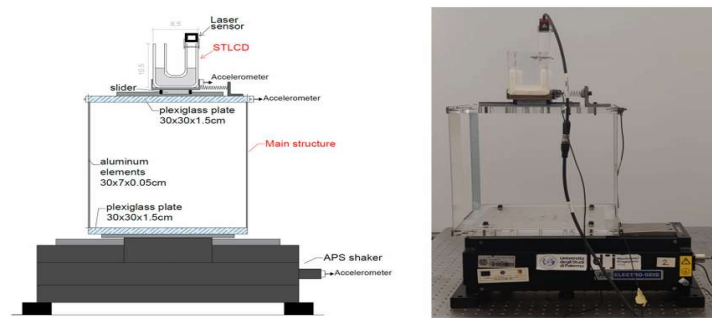


Figure 2.26: Small-scale model of the STLCD-controlled structure. (Masnata *et al.* 2024)

An experimental comparison was conducted between an uncontrolled structure, a TLCD-controlled structure, a TMD-controlled structure, and an STLCD-controlled structure under resonance conditions. The STLCD demonstrated the highest performance, reducing acceleration by up to 70% under harmonic ground excitation, as shown in Figure 2.27.

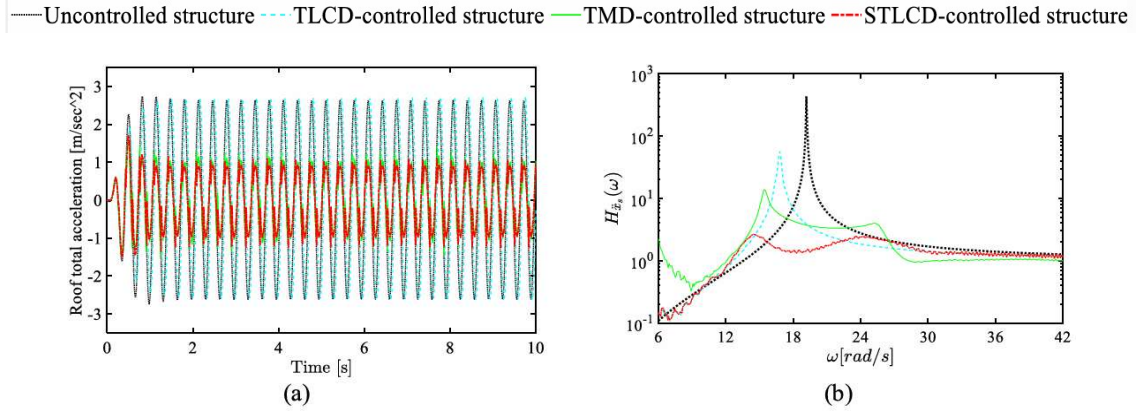


Figure 2.27: 3 Response of the STLCD-controlled structure compared to the uncontrolled structure, the TLCD-controlled structure and TMD-controlled structure: a) roof total acceleration in resonance conditions and b) FRF of the roof acceleration. (Masnata *et al.*, 2024)

Gur *et al.* (2014) conducted a study aimed at enhancing the performance of Compliant Tuned Liquid Column Dampers (CTLCDs) by replacing the conventional linear spring with a shape memory alloy (SMA) spring for seismic vibration control, particularly in stiff structures. The use of SMA springs improves energy dissipation due to their super-elastic hysteresis behavior. Optimal design parameters for the SMA-compliant TLCD were determined through nonlinear random vibration analysis using stochastic linearization. Parametric studies indicated that, in addition to the tuning ratio and head-loss coefficient, there exists an optimal SMA strength that maximizes the control performance. As SMA has an additional source of energy dissipation through hysteretic behaviour of SMA springs during cyclic loading, enhances the overall damping performance. Overall, the SMA-LCD consistently outperforms the compliant LCD in mitigating broadband seismic vibrations in short-period structures. However, time-history analyses based on a limited set of ground motions indicate the need for a more extensive investigation using a broader dataset to fully validate the robustness of the observed optimal performance.

Subsequent experimental studies on tuned liquid dampers were also conducted. For instance, Pandey *et al.* (2019) investigated the performance of a compliant TLD (CTLTD) in a short-period structure. The compliant mechanism incorporated an array of symmetrically arranged elastomeric pads to achieve precise tuning. The CTLTD successfully reinstated resonant sloshing and wave-breaking phenomena, both of which are critical for effective seismic energy dissipation. These features enhance the damper's performance under varying ground motion characteristics. The compliant TLD achieved notable reductions in structural vibrations when subjected to seismic ground motions. The results confirmed its robustness

across varying hazard levels, making it suitable for real-world applications. In 2025 study, Sardar and Chakraborty introduced an innovative vibration control system called the Compartmentalized Compliant Tuned Liquid Mass Damper (CCTLMD), aimed at improving the performance of traditional TLMDs in offshore structures like jacket platforms. To overcome the limitations of shallow water depths, which often cause inefficient energy dissipation due to thrashing. They proposed a geometry modification by dividing the tank into multiple compartments. This design helps maintain deep tank conditions, even with fluctuating water levels, thereby increasing the effective impulsive mass and enhancing damping performance. The CCTLMD demonstrated significant reductions in deck vibrations (up to 28.33%) across different loading scenarios and showed robust performance regardless of changes in sea state. It also outperformed conventional TLMDs under seismic excitation, as evidenced in a comparative study with building structures, referencing findings by Pandey *et al.* (2022). Although the results are promising, the study highlights the need for further investigation through experimental validation and advanced 3D modelling to assess real-world offshore applications more accurately.

Recent studies have increasingly focused on integrating inerters with compliant damping systems to enhance structural vibration control. Pandey and Mishra (2021) proposed the Compliant Liquid Column Inerter Damper (CLCID) by combining an inerter with the traditional CLCD. Through nonlinear dynamic analysis of both SDOF and MDOF systems under various ground motions, the CLCID showed 50–80% reduction in peak and r.m.s. responses, significantly outperforming the conventional CLCD. The system also demonstrated strong robustness and reduced displacement of the liquid column and container, making it suitable for practical implementation in both low-rise and tall buildings. However, the study primarily focused on numerical simulations and idealized modeling, without experimental validation or consideration of implementation challenges such as mechanical complexity and space constraints. Similarly, Das *et al.* (2023) introduced the Compliant Deep Tank Damper Inerter (CDTDI) using an overhead fire water tank, achieving 25% peak displacement and 21% floor acceleration reduction in RC buildings. The system's performance improved with building height due to increased flexibility. Building on this, Das *et al.* (2025b) studied the Compliant Liquid Damper-Inerter (CLDI) under stochastic wind loads, reporting up to 93.81% FRF reduction. However, the study had several limitations, including the use of a simplified single-degree-of-freedom (SDOF) model to represent a 20-story building, the assumption of ideal inerter behavior characterized by a linear force-acceleration relationship, and the reliance

on Gaussian white noise and the Kaimal spectrum for wind modeling, which may not accurately reflect real-world turbulence or non-stationary wind effects. Overall, while these studies highlight the potential of compliant inerter-based systems, further research is needed to address modeling limitations and validate their performance under realistic conditions.

### 2.5.2. Compliant TLCDs as Hybrids

Masnata and Pirrotta (2024) investigated the effect of a sliding-tuned liquid column damper and a base isolation system. The sliding mechanism involved a spring-dashpot and roller system supporting the TLCD, as shown in Figure 2.29 (a). This sliding system was also connected to a Base isolator (BI) system. A numerical and analytical study was conducted to compare the effectiveness of the base isolation (BI) system alone and in combination with various dampers, including a Tuned Mass Damper (TMD), a Tuned Liquid Column Damper (TLCD), and a Semi-Tuned Liquid Column Damper (STLCD).

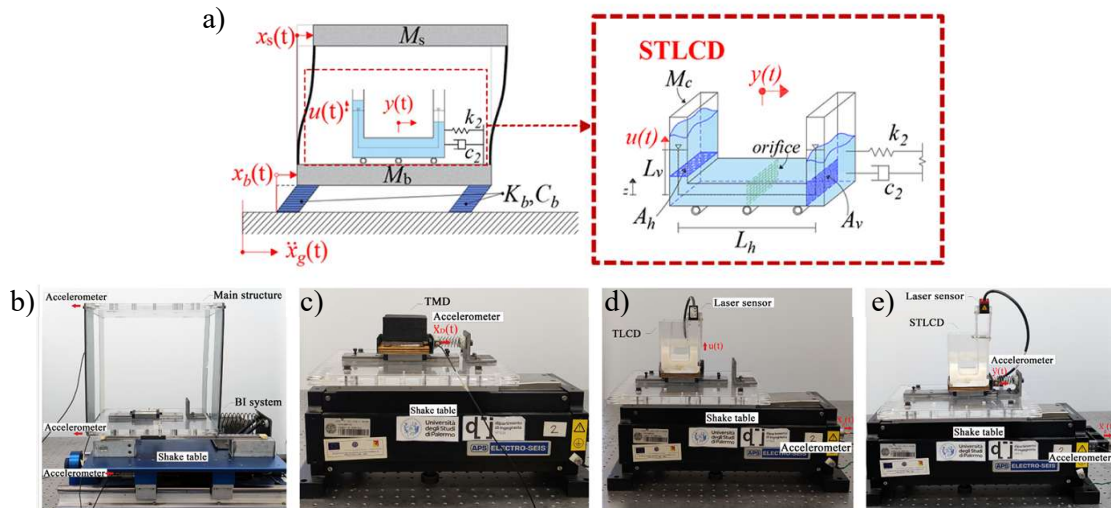


Figure 2.28: (a) BI & STLCD strategy with detail STLCD and Scale models of the subsystems: (b) BI system; (c) TMD; (d) TLCD; (e) Proposed STLCD device. (Masnata and Pirrotta. 2024)

Unlike TLCD, which is mainly controlled by natural frequency and head loss coefficient, STLCD has additional characteristics. STLCDs are influenced not only by the natural frequency but also significantly by the damping ratio of the container. This means that, by adjusting the liquid length, STLCDs allow for extra control over damping, which helps absorb energy more effectively. The added damping effect makes STLCDs more versatile in reducing vibrations, as they can better control oscillations than TLCDs. 44 Ground motion from the P-695-FF database as base excitation has been considered. The selected ground motions were recorded during various seismic events between 1971 and 1999 across different countries, with

magnitudes ranging from M6.5 to M7.6 and peak ground accelerations between 0.18g and 0.58g.

In numerical and analytical studies, the STLCD reduces base displacement by 61%, outperforming TMD (59%) and TLCD (34%) at low damping (0.01). As the BI damping increases, all the devices show minimum benefits. From the 44 ground motions, STCD and TMD show similar performance, significantly reducing the base and roof displacement.

A small-scale structural model was designed to test the effectiveness of BI & STLCD, BI & TMD, and BI & TLCD strategies, as shown in Figure 2.29 (b-e). The spring helps tune the structure and dampen it with the dashpot. The experimental data were compared with the numerical data to verify the accuracy. The experimental results matched with numerical results, confirming that the analytical model accurately predicted the BI & STLCD system. The BI & STLCD system significantly reduced base displacements by up to 90%, outperforming the TLCD and matching the performance of the TMD with the same mass. Roof displacements and relative displacements were also effectively reduced. The STLCD preserved the base isolation functionality while improving vibration control. All control devices (TMD, TLCD, and STLCD) improved the BI structure's performance, but the STLCD showed the best results. Unlike the TLCD, which had limited effectiveness, the STLCD provided better damping control while using water as a mass, making it practical and cost-effective.

This makes them more adaptable, cost-effective, and reliable over long periods. Furthermore, advancements such as multi-TLCD systems, hybrid TLCD-TMD combinations, and Compliant Tuned Liquid Column Ball Dampers (Compliant-TLCBDs) have enhanced their performance, enabling their application in a wide range of structures subjected to dynamic loads.

## 2.6. Gaps in the Literature

Recent advancements in liquid-based and compliant damping systems have significantly improved the efficiency and adaptability of vibration control in structures, particularly under seismic and wind loads. These innovations, such as compliant mechanisms, inerter integration, and compartmentalized dampers, offer enhanced performance, space efficiency, and cost-effectiveness compared to traditional TLCDs.

However, several limitations still persist despite the promising advancements in liquid-based and compliant damping systems. Tuning remains a significant challenge, particularly for short-period (stiff) structures, where achieving the necessary natural frequency often requires impractically short liquid columns. While many proposed systems demonstrate encouraging results through simulations, experimental validation is frequently limited or absent. Practical issues such as space constraints, complex installation requirements, and increased mechanical complexity. Maintenance demands and cost factors, particularly when using advanced materials like magnetic fluids, also pose concerns. The high cost of magnetic fluids, along with the need for continuous power supply and risks of sedimentation or biological contamination, restricts their real-world applicability. Moreover, the effectiveness of these damping systems tends to diminish as the inherent structural damping increases, making them less suitable for structures with significant nonlinear behavior. Additionally, many studies rely on simplified models and idealized loading conditions, which may not fully capture the complexity of real-world dynamic responses. There is also a lack of comprehensive analysis on how different types of ground motion characteristics influence TLCD performance, and limited experimental studies have been conducted using past earthquake data. Furthermore, the influence of varying fluid densities on damper efficiency remains underexplored. In spring-connected systems, heavy structural damping or predominant nonlinear responses may lead to diminished control effectiveness, failing to reduce peak responses during strong excitations. Therefore, while these systems represent a substantial leap forward, further research is essential to overcome these practical and technical limitations for reliable real-world implementation.

## Chapter 3

### WORK METHODOLOGY

#### 3.1. Overview

This chapter discusses the basic methodology and considerations to improve the performance TLCD. Analyzing the building's dynamic properties, such as natural frequency, damping ratio, and its fundamental to predicting its response to seismic activity. These characteristics are governed by the structure's mass, stiffness, and geometry. For a Tuned Liquid Column Damper (TLCD) to perform effectively, its parameters must be fine-tuned to align with the building's natural frequency and damping behavior. Ultimately, the integration of TLCDs, guided by a thorough understanding of dynamic properties, enhancing the seismic performance of structures.

#### 3.2. Experimental Program

For the application to short-period structures, a novel form of Tuned Liquid Column Damper (TLCD) was developed, incorporating a compliant U-tube partially filled with water and a freely moving solid ball inside the tube. This advanced configuration aims to enhance damping performance by simultaneously utilizing fluid dynamics and the added mass effect of the ball to increase energy dissipation. The water inside the U-tube oscillates in reaction to structural vibrations caused by dynamic external forces like earthquakes or wind. Meanwhile, the movement of the ball introduces added inertia, impact forces, and turbulence, which significantly enhance the damping effect and improve the system's energy absorption capacity. To further increase the effectiveness, a compliant mechanism was integrated into the setup, enabling better adaptability to the rapid displacement responses typical of short-period structures. This compliant arrangement allows relative motion within the damper components, contributing to improved energy transfer and reducing the restoring forces that could otherwise reintroduce motion.

To assess the performance of the hybrid damping system, a comprehensive parametric study was carried out using 43 scaled ground motion records of varying characteristics. These records represent a diverse range of seismic scenarios with varying frequency contents, peak ground accelerations, and intensity levels. The results demonstrated that the CTLCD with a

ball significantly outperformed conventional TLCDs, particularly in low-rise or stiff structures that are more susceptible to high-frequency ground motions. The system was effective in suppressing peak displacements, reducing acceleration responses, and shortening the vibration duration after shock events. This innovative approach presents a promising and adaptable solution for improving the seismic resilience and dynamic performance of modern civil infrastructure, particularly in cases where traditional dampers are less effective against high-frequency input motions.

### **3.3. Fabricated Damper Device**

The fabrication of a scaled structural model is a critical component of this experimental study. A three-story scaled building model has been constructed to serve as the primary structure for vibration control experiments. The model is meticulously designed to replicate the key dynamic characteristics of a typical low-rise building. Its fabrication involves the strategic selection of materials and dimensions to achieve dynamic similitude while adhering to the practical limitations of laboratory testing. Passive control devices, such as Tuned Liquid Column Dampers (TLCDs), along with additional components like compliant mechanisms, are also incorporated and described. These elements offer the flexibility to conduct a broad range of tests under various configurations, enabling an in-depth investigation into the impact of damping systems on structural response. The fabrication process is guided by theoretical calculations, scaled parameters, and practical construction techniques to ensure that the resulting model accurately reflects the desired physical and dynamic behavior. This fabricated model forms the foundation for the subsequent experimental and analytical studies presented in the following sections.

#### **3.3.1 *Governing Equation of the building***

To evaluate the response of the fabricated structure under dynamic excitation, it is crucial to establish the governing equations of motion. The structure is idealized as a three-degree-of-freedom (3-DOF) shear building model, where each floor is represented as a lumped mass and the interconnecting columns are modeled as linear springs and viscous dampers. The resulting equations of motion for this multi-degree-of-freedom (MDOF) system are expressed in matrix form, as presented in Eq. (3.1).

$$[M] \{\ddot{x}\} + [C] \{\dot{x}\} + [K] \{x\} = -M r \{\ddot{x}_g\} \quad (\text{Eq. 3.1})$$

Where,  $M$ ,  $C$ , and  $K$  are the mass, damping, and stiffness matrices respectively and  $\ddot{x}$ ,  $\ddot{x}_g$ ,  $\dot{x}$ , and  $x$  represents the acceleration, ground acceleration, velocity and displacement respectively. The influence coefficient vector is given by  $r = [0 \ 0 \ 0 \ 1]^T$  and  $x = [x_l \ x_b \ x_c \ x_s]^T$  where  $x_l$  is the liquid column displacement,  $x_b$  is the ball displacement,  $x_c$  is the compliant (damper) displacement and  $x_s$  is the structure displacement. This equation captures the dynamic interaction between the structure and seismic ground motion, providing a basis for numerical simulation and structural response analysis.

### 3.3.2 Equation of motion for TLCBD

Building upon the traditional TLCD, Al-Saif et al. (2011) proposed the Tuned Liquid Column Ball Damper (TLCBD), which introduces a rolling ball in place of a fixed orifice. This enhancement acts as a moving orifice, providing variable resistance and improved energy dissipation. In this configuration, the fixed orifice in the TLCD is replaced by a rolling ball, which acts as a moving orifice. This modification enhances the energy dissipation mechanism, making the system more effective in controlling structural vibrations. The governing equation for the fluid motion in the TLCBD is given in Eq. (3.2)

$$m_f \ddot{y} + C_t \dot{y} + 2pqAy_s + \alpha m_f \ddot{x}_g = 0 \quad (\text{Eq. 3.2})$$

where,  $m_f$  is the mass of the fluid,  $C_t$  is the total damping coefficient,  $A$  is the cross-sectional area of the liquid column,  $y$  is the liquid displacement,  $y_s$  is the relative displacement of the structure,  $\alpha$  is a coupling coefficient, and  $\ddot{x}_s$  is the acceleration of the structure. This equation models the fluid dynamics inside the column influenced by the structural motion and gravity. The equation of motion for the rolling ball, which acts as the variable orifice is given in Eq. (3.3)

$$\left(m_b + \frac{J_c}{R_b^2}\right) \ddot{x}_b + d_{eq} \dot{x}_b = \frac{J_c}{R_b^2} \ddot{x}_s + d_{eq} \dot{y} + 2pgA_b y \quad (\text{Eq. 3.3})$$

Here,  $m_b$  is the mass of the ball,  $J_c$  is the moment of inertia of the ball,  $R_b$  is the ball radius,  $x_b$  is the ball displacement, and  $d_{eq}$  is the equivalent damping due to friction and fluid-structure interaction. This equation captures the dynamic behavior of the rolling ball under the influence of the host structure and fluid motion. Finally, the coupled equation of motion for the host structure integrated with the TLCBD is expressed in Eq. (3.4)

$$\left(m_s + m_f + \frac{J_c}{R_b^2}\right) \ddot{x}_s + c_s \dot{x}_s + k_s x_s + \alpha m_f \ddot{y} - \frac{J_c}{R_b^2} \ddot{x}_b = f_{ext}(t) \quad (\text{Eq. 3.4})$$

where,  $m_s$ ,  $c_s$ , and  $k_s$  are the mass, damping, and stiffness of the host structure, and  $f_{ext(t)}$  is the external excitation (e.g., from seismic forces). This coupled equation describes the total dynamic response of the structure considering the interactions between the structure, the fluid column, and the rolling ball.

### 3.3.3 *Building Model*

Following the theoretical formulation and component-level modeling, a small-scale, three-story compliant frame structure was fabricated and experimentally tested to validate the integrated vibration control system. This model represents the physical realization of the structural system discussed earlier and is specifically developed to evaluate the performance of a Compliant Tuned Liquid Column Damper (CTLCD) integrated with an internal solid ball mechanism. The entire structure is fabricated using mild steel (Fe 250), chosen for its favorable machinability and well-defined material properties including a density of  $7850 \text{ kg/m}^3$  and Young's modulus of 210 GPa making it well-suited for scaled dynamic analysis.

The structure was designed to mimic the dynamic characteristics of a short-period system, with a fundamental natural time period of approximately 0.3 seconds, which is representative of low-rise and stiff buildings. The inter-story height was maintained at 400 mm (center-to-center), providing geometric regularity for simplified modal analysis and fabrication. The frame configuration includes four rigidly connected slabs and four vertical columns, forming a stable and continuous structure that closely replicates real-world boundary conditions. The self-weight of the fabricated frame, including the base slab, amounted to 68.36 kg. However, to meet the target total mass of 100 kg required for realistic seismic response analysis additional concentrated masses were strategically introduced at each floor level. As shown in Figure 3.1, one centrally placed 10 kg mass with a diameter of 15.7 mm was positioned, accompanied by four distributed 1.5 kg masses (each 6 mm in diameter) across the first, second, and third floors. This configuration ensured an appropriate mass distribution that simulates real building behavior under dynamic excitation. Each column had a rectangular cross-section measuring  $6 \text{ mm} \times 25 \text{ mm}$ , contributing approximately 5.65 kg to the total mass across all four columns. The slabs, each with a thickness of 10 mm and a plan dimension of  $500 \text{ mm} \times 400 \text{ mm}$ , accounted for a total slab mass of 47.1 kg. These dimensions and properties are detailed in Table 3.1, which summarizes all geometric and material characteristics of the model components.

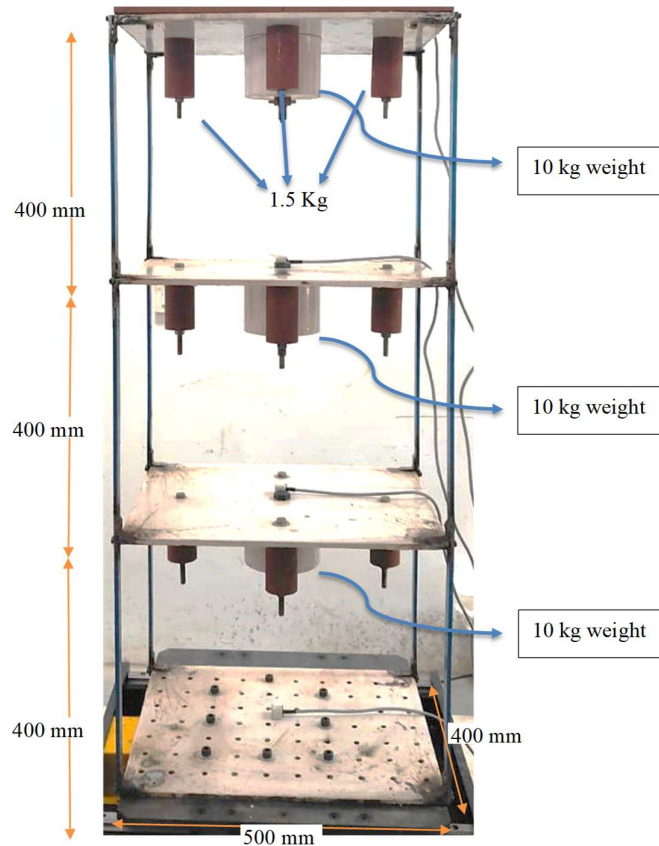


Figure 3.1: Experimental set up of 3-story frame structure with the additional weight of 10 kg at center and 1.5 kg weight at the edges.

Table 3.1: Dimension of the model

Model Component	Dimensions (mm)	Remarks
Ply-Board (wood)	500 x 400 x 16	Placed on top story
Slab on each floor	500 x 400 x 10	Floor plate per story
Column	6 x 25 x 400	Slender vertical support
10 kg Weight (per story)	15.7 $\phi$	Circular weight
Four 1.5 kg Weights (per story)	6 $\phi$	4 circular weights per story

### 3.3.4 Tuned Liquid Column Damper (TLCDs)

Tuned Liquid Column Dampers (TLCDs) are a modified version of Tuned Liquid Dampers (TLDs), designed to mitigate structural vibrations under dynamic loading conditions such as earthquakes and wind. As discussed in Chapter 2, a TLCD typically contain a U-shaped column filled partially with liquid and includes an orifice to regulate the flow, thus introducing head loss and improving energy dissipation. In the present experiment, a moving orifice is employed to further enhance energy dissipation. This is achieved by increasing resistance to fluid flow and by utilizing frictional interaction between the fluid and a solid ball placed inside the tube. According to Al-Saif *et al.* (2011), steel balls have shown superior performance in

improving the damping efficiency of TLCDs compared to traditional setups. Based on this, a steel ball with a diameter of 1.25 inches (31.75 mm) is used in this study. The acrylic tube used in the TLCD has an inner diameter of 40 mm, yielding a ball-to-tube diameter ratio ( $R_{bt}$ ) of 0.8. This ratio falls within the optimal range for promoting effective flow obstruction and dynamic interaction, thereby enhancing the damping performance. The TLCD consists of a container partially filled with liquid; when the structure undergoes vibration, the liquid sloshes out of phase with the structural motion, producing counteracting forces that reduce the amplitude of the response. The depth ratio and other geometric characteristics (Eq. 2.7) determine the damper's performance. The TLCD employed in this system, shown in Figure 3.2(a), is fabricated using three segments of acrylic tubing joined by two elbow connectors. The horizontal length ( $B$ ) between the center points of the vertical columns is 48 cm, and the total liquid-filled length ( $L$ ) is 100 cm, resulting in a length ratio of 0.5.

To effectively analyze the performance of this damping system on short-period structures, a compliant mechanism was developed. Previous researchers including Ghosh and Basu (2004), Gur *et al.* (2014), and Pandey *et al.* (2019) have numerically and experimentally demonstrated the potential of compliant mechanisms for vibration control in such structures. In this study, a unidirectional compliant model was developed, incorporating Shape Memory Alloy (SMA) springs to facilitate controlled motion and energy dissipation. As illustrated in Figure 3.2 (b), the compliant mechanism consists of six rods. Rods 1 and 2 connect the structural components that support the U-tube, these components were designed using SolidWorks software and manufactured using a 3D printer. Rods 3 and 4 are fixed in place, providing the necessary stability to the structure, while allowing sliding motion of attached components. Rods 5 and 6 constitute the core of the compliant mechanism, each connected to springs that facilitate the restoration of the structure to its original position following displacement. This self-centering capability is crucial for post-earthquake recovery. Springs are strategically attached between the sliding components, creating a functional, flexible model that effectively simulates the restoring behavior found in real-world structural systems. The compliant mechanism is fully integrated with the U-tube, and the steel ball is placed within the tube. This innovative system is designed to maximize energy dissipation and enhance the seismic performance of short-period structures.

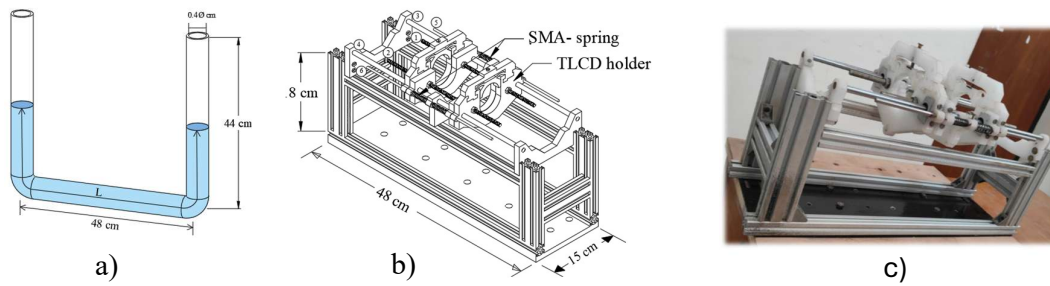


Figure 3.2: Schematic representation of a) TLCD configuration and b) Compliant Mechanism and c) compliant experimental set up.

### 3.3.5 Shape Memory Alloy (SMA)

The idea of shape memory alloys (SMAs) is that it not only offers the flexibility needed for tuning system frequencies, but also help reduce vibrations by absorbing energy through internal phase changes when subjected to repeated loading. This dual functionality significantly enhances the control performance of the structural system. The effectiveness of the SMA-integrated TLCD under seismic excitation is assessed through nonlinear random vibration analysis, which incorporates statistical linearization of the SMA's hysteretic force-deformation behavior due to phase transitions, along with energy dissipation from fluid flow resistance across the orifice.

A comprehensive parametric study of the system's stochastic response is conducted to identify optimal design parameters for maximizing damping performance by Gur *et al.*, 2014. Conventional damping systems often suffer from limitations such as mechanical wear and the need for regular maintenance due to moving parts. Over time, traditional linear springs lose their elasticity, leading to reduced performance and potential system failure. In contrast, SMAs offer a promising alternative by eliminating the need for complex mechanical components. Compliant tuned liquid column dampers (TLCDs) with SMA integration provide a more durable and maintenance-free solution, ensuring long-term structural vibration control efficiency. To address the challenge of residual displacements after seismic events, in this paper a self-centering SMA mechanisms in the compliant system will be studied. These systems not only dissipate energy but also restore the structure to its original position post-earthquake. Examples include phase transformation dampers using SMAs, energy dissipation restraint systems, and spring assemblies equipped with friction-based re-centering mechanisms. Such advancements enhance both the resilience and reliability of modern damping devices in structural applications. In this experiment nickel–titanium alloy or Nitinol. and the spring

stiffness of 213.82 N/m have been incorporated. This spring is fitted in the compliant mechanism as shown in Figure 3.3. The weights of the damping mechanism CTLCD is given in Table 3.2.

Table 3.2: The weight of the components measured in the experiment.

Components	Weight (kg)
Compliant mechanism	5.60
TLCD	0.88
Steel ball	0.131
Water	1.257
Scaled Three-story structure	100.00



Figure 3.3: Representation of the building with the CTLCD with load provision on each story, placed shake table experimental model.

This model has integrated a Compliant Mechanism and a ball element within the tube. The compliant mechanism allows controlled deformation, enabling enhanced interaction between the ball and fluid motion, which leads to improved damping performance over a wider frequency range. The ball moves within the liquid column and generates additional energy dissipation through fluid structure interactions and impact dynamics. This hybrid design integrates the sloshing motion of the liquid, the kinetic energy absorption from the moving ball, and the elastic deformation of the compliant structure. By tuning key parameters, such as liquid depth, ball mass, tube geometry, and the stiffness of the compliant element, the system can be optimized to align with the dynamic characteristics of the structure. The CTLCD is especially

suiting for multi-degree-of-freedom (MDOF) systems and offers significant potential for use in buildings, towers, and other critical infrastructure to enhance their seismic performance.

### **3.4. Considered Ground Motions**

The ground motion data for this study were sourced from the Pacific Earthquake Engineering Research Center (PEER) ground motion database. Key seismic parameters considered include a target peak ground acceleration (PGA) of approximately 0.5g, a maximum allowable displacement of less than 100 mm, and a natural period of 0.3 seconds to ensure compatibility with the shake table setup. These criteria are critical for evaluating structural resilience and optimizing performance under seismic loading. Ground motions were meticulously selected based on magnitude (4.5–7.5), source-to-site distance (10–50 km), and specific record sequence numbers (RSNs). Each selected record was scaled to achieve the desired PGA and natural period, ensuring a realistic representation of seismic demands. The scaling procedure and data extraction methods were adapted from Abhishek (2024). Conditioning of the ground motions involved amplitude and time scaling, frequency matching using Fast Fourier Transform (FFT) analysis, and displacement adjustments using Seismosignal software to maintain displacements within the 50 to 70 mm range for safe shake table testing. Critical ground motion parameters, including amplitude, frequency content, duration, and energy-related measures were comprehensively analyzed to ensure the reliability of seismic performance assessments. This systematic and rigorous approach provided a robust dataset for accurate evaluation of the structure's behavior under realistic seismic scenarios.

#### **3.4.1 *Ground Motion Properties***

A total of 43 ground motions were selected from the database based on specific criteria to ensure suitability for seismic analysis. The selection was guided by a target peak ground acceleration (PGA) of approximately 0.5g and the predominant natural time period, with the maximum duration of each motion limited to 60 seconds. To align with seismic force requirements, the recorded PGA values were scaled within the range of 0.45g to 0.65g. Additionally, the maximum displacement responses were maintained within 50–70 mm to remain within the operational limits of the shake table. Understanding seismic loading and designing earthquake-resistant structures requires careful analysis of various ground motion parameters. These include amplitude parameters, which describe the strength of shaking and encompass peak ground acceleration (PGA), and peak ground displacement all representing the maximum values recorded during an event. The frequency content is also critical, as it

reflects how seismic energy is distributed across different frequencies. This can be assessed using response spectra (showing peak responses for oscillators with various natural periods), Fourier spectra (amplitude vs. frequency plots derived via Fourier Transform), and the predominant period, which indicates the frequency range with the highest energy concentration. Another critical parameter is duration encompassing both bracketed duration (the time between the first and last exceedance of a specified acceleration threshold) and significant duration (commonly defined as the time interval over which 5% to 95% of the total energy of the motion is accumulated). Additionally, various ground motion intensity measures such as root mean square (RMS) acceleration, velocity, and displacement; Arias intensity; cumulative absolute velocity (CAV); velocity and acceleration spectrum intensities; effective peak acceleration (EPA); and effective peak velocity (EPV) are employed to comprehensively characterize and compare seismic input motions. These parameters collectively help characterize the earthquake input and ensure that the structural response is realistically and effectively captured in the analysis. The considered 43 ground motions are given in Table 3.2, with their properties. The peak ground acceleration (PGA) is the maximum recorded acceleration at a site is expressed, its unit is generally expressed in gravity ( $g$ ). Higher the value of PGA, stronger will be the shaking and it is important to identify the immediate impact on the building. Peak ground displacement (PGD) is the maximum absolute ground movement (displacement) during an earthquake, typically measured in centimeters (cm) or meters (m). The velocity range that typically influences the dynamic behavior of structures lies between 0.14 m/s and 0.32 m/s. In the present study, ground motion GM53, illustrated in Figure 3.4 was selected for detailed analysis, with its acceleration, velocity, and displacement time histories plotted. The acceleration profile indicates a peak ground acceleration (PGA) of 0.6  $g$ , reflecting a strong seismic event. The displacement time history shows a peak ground displacement (PGD) of 0.012 m. These metrics collectively offer valuable insights into the intensity and dynamic characteristics of the GM53 record. The Figure 3.4 illustrates a time history of acceleration, showing how the acceleration (measured in units of  $g$ , where  $1g \approx 9.81 \text{ m/s}^2$ ) varies with time over a 12-second duration. The signal exhibits a typical earthquake-like pattern with a noticeable increase in acceleration around 2 to 3 seconds, indicating the arrival of strong ground motion or dynamic excitation. The peak acceleration approaches values close to  $\pm 0.5g$ , after which the amplitude gradually decreases, reflecting a decay in vibration intensity over time. This reduction in amplitude suggests the presence of damping, either inherent in the system or induced through vibration control mechanisms.

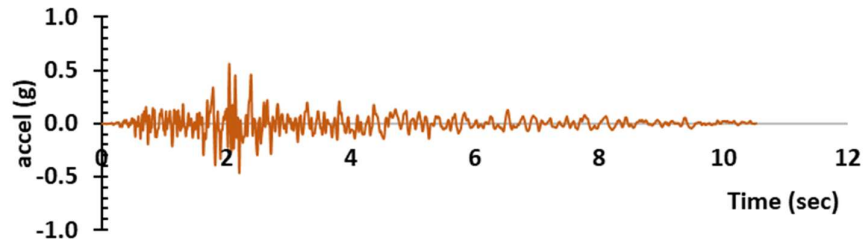


Figure 3.4: Ground acceleration Time History graph of GM53.

### 3.4.2 *RMS (Root Mean Square) acceleration*

RMS is a statistical measure that reflects the average magnitude of acceleration over time, accounting for both positive and negative fluctuations during seismic shaking. It is calculated by taking the square root of the mean of the squared acceleration values over the duration of interest. Unlike peak acceleration, which captures only the single largest value, RMS acceleration provides a more comprehensive representation of the overall energy content or intensity of the motion. In seismic response analysis, RMS acceleration is particularly valuable because it captures the cumulative effect of shaking, which relates to structural fatigue, damage potential, and vibration comfort levels. A high RMS acceleration indicates that the structure was subjected to intense, sustained shaking, even if the peak value was not exceptionally large.

### 3.4.3 *Response Spectrum*

It represents the maximum response of an idealized spectrum of single-degree-of-freedom (SDOF) systems, each with varying natural periods but identical damping ratios, subjected to the same earthquake ground motion at their bases. As per IS 1893 (Part 1):2016, the response considered is typically the maximum absolute acceleration.

Figure 3.5, presents the acceleration response spectra for a set of 43 ground motion (GM) records. The x-axis represents the structural time period (in seconds), while the y-axis indicates the peak acceleration response (in g) of a single-degree-of-freedom system subjected to these motions. Each thin gray line represents the spectrum of an individual ground motion, while the red line indicates the average spectral response across all 43 records. The shaded blue regions represent one standard deviation above (dashed blue) and below (dashed blue) the mean (solid red) response, capturing the variability among the motions. The plot shows that the maximum acceleration typically occurs in the short-period range (approximately 0.1–0.3 seconds), which is critical for the design and assessment of low-rise and stiff structures. The spectrum flattens as the period increases, indicating reduced dynamic amplification for longer-period structures.

The response spectrum offers critical insights into the seismic demand characteristics associated with the selected set of ground motions.

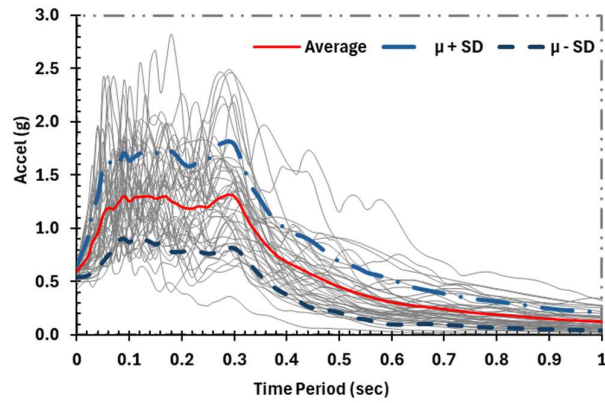


Figure 3.5: 43 Ground Motions with Mean and  $\pm 1$  Standard Deviation of acceleration Response Spectrum.

Table 3.3: Ground motion parameters considered

Sl.no.	Name	GM (Sl.No.)	Station	Year	Magnitude	PGA (g) (Scaled)	PGV (cm/sec) (Scaled)	Vm/Am (sec)	Predominant period (sec)
1	Ancona-09	GM 01	Ancona-Rocca, Italy	1972	4.7	0.52	0.18	0.034	0.3
2	Cape Mendocino	GM 03	Petrolia	1992	7.01	0.59	0.2	0.035	0.26
3	Coalinga-05	GM 07	Oil City	1983	5.77	0.58	0.15	0.026	0.1
4	Coyote Lake	GM 08	Gilroy Array #4	1979	5.74	0.62	0.3	0.05	0.12
5	Hollister-03	GM 13	Hollister City Hall	1974	5.14	0.62	0.2	0.032	0.2
6	Imperial Valley-06	GM 14	Bonds Corner	1979	6.53	0.6	0.2	0.033	0.18
7	Kobe	GM 17	Nishi-Akashi, Japan	1995	6.9	0.53	0.32	0.061	0.28
8	L'Aquila	GM 19	Centro Valley, Italy	2009	6.3	0.64	0.31	0.048	0.08
9	Lazio Abruzzo (aftershock 1)	GM 20	Villetta Barrea, Italy	1984	5.5	0.58	0.21	0.037	0.3
10	Livermore-02	GM 21	Livermore, Fagundas Ranch	1981	5.42	0.62	0.22	0.036	0.16
11	Loma Prieta	GM 22	Bran, California	1989	6.93	0.53	0.4	0.077	0.28
12	Morgan Hill	GM 23	Halls Valley	1984	6.19	0.65	0.3	0.048	0.28
13	N Palm Springs	GM 24	Whitewater Trout Farm	1986	6.06	0.62	0.28	0.047	0.12
14	Parkfield-02	GM 28	Parkfield - Stone Corral 1E	2004	6	0.68	0.23	0.034	0.04

15	Superstition Hills-02	GM 30	Superstition Mtn Camera	1987	6.54	0.57	0.15	0.026	0.16
16	Umbria Marche	GM 32	Colfiorito, Italy	1997	6	0.65	0.18	0.028	0.06
17	Westmorland	GM 33	Salton Sea Wildlife Refuge	1981	5.9	0.64	0.18	0.029	0.06
18	Yountville	GM 35	Napa Fire Station #3	2000	5	0.65	0.28	0.044	0.24
19	Westmorland	GM 43	Brawley Airport, 225	1981	5.6	0.56	0.21	0.038	0.06
20	Mammoth Lakes-10	GM 44	Convict Creek, 90	1983	6	0.58	0.3	0.053	0.26
21	Imperial Valley-07	GM 45	El Centro Array #6, 140	1979	6.6	0.65	0.31	0.049	0.2
22	Coalinga-04	GM 46	Skunk Hollow, 360	1983	6.7	0.61	0.29	0.048	0.3
23	Imperial Valley-07	GM 50	Holtville Post Office, 225	1979	6.6	0.52	0.36	0.071	0.14
24	Coalinga-04	GM 51	Skunk Hollow, 270	1983	6.7	0.65	0.16	0.025	0.1
25	Mammoth Lakes	GM 52	Convict Creek, 90	1983	6	0.65	0.17	0.027	0.06
26	Westmorland	GM 53	Superstition Mtn Camera, 45	1981	5.9	0.56	0.15	0.027	0.04
27	Taiwan SMART	GM 54	SMART1 O07, EW	1981	6.9	0.56	0.08	0.014	0.04
28	Coalinga-05	GM 55	Transmitter Hill, 270	1983	6.7	0.65	0.17	0.027	0.26
29	Victoria Mexico	GM 56	Cerro Prieto, 45	1980	6.1	0.56	0.1	0.018	0.06
30	N. Palm Springs	GM 59	Anza Fire Station, 225	1986	6.1	0.5	0.27	0.056	0.3

31	Big Bear	GM 60	Desert Shores, 90	1992	6.5	0.63	0.12	0.019	0.12
32	Big Bear	GM 61	Hemet Fire Station, 90	1992	6.5	0.49	0.08	0.016	0.14
33	Whittier Narrows	GM 62	La Puente - Ringrove Av, 15	1987	5.9	0.65	0.19	0.03	0.18
34	Whittier Narrows	GM 64	LA - S Grand Ave, 90	1987	5.9	0.55	0.23	0.042	0.16
35	Whittier Narrows	GM 66	Glendale - Las Palmas, 177	1987	5.9	0.65	0.23	0.036	0.14
36	Whittier Narrows	GM 67	Castaic - Old Ridge Route, 0	1987	5.9	0.65	0.21	0.033	0.18
37	Chalfant Valley	GM 69	Zack Brothers Ranch, 270	1986	6.2	0.65	0.17	0.027	0.06
38	N. Palm Springs	GM 70	Rancho Cucamonga - Law and Justice Center FF Foothill and Haven, 0	1986	6.1	0.66	0.13	0.02	0.08
39	N. Palm Springs	GM 71	Puerta La Cruz, 258	1986	6.1	0.63	0.29	0.047	0.3
40	N. Palm Springs	GM 72	Cranston Forest Station, 225	1986	6.1	0.65	0.16	0.025	0.06
41	N. Palm Springs	GM 73	Anza - Tule Canyon, 270	1986	6.1	0.65	0.24	0.037	0.14
42	Trinidad offshore	GM 77	Rio Dell Overpass W Ground, 0	1983	5.8	0.56	0.21	0.039	0.24
43	Trinidad offshore	GM 78	Rio Dell Overpass E Ground, 0	1983	5.8	0.62	0.27	0.044	0.22

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### 3.5. Shake Table Test

To simulate the ground motion of an earthquake, shake table are used. The table consist of a platform that can move in single or multi-axis. The 3-story scale structure is installed on the shake table of Structures Laboratory of Thapar Institute of Engineering and Technology, Patiala, Punjab. The structure is anchored to the shake table using steel bolts, effectively restraining all degrees of freedom at the base of each column. The shake table system comprises an application interface, a control unit, and the table's movable components, all functioning in synchrony, as illustrated in Figure 3.8(a).

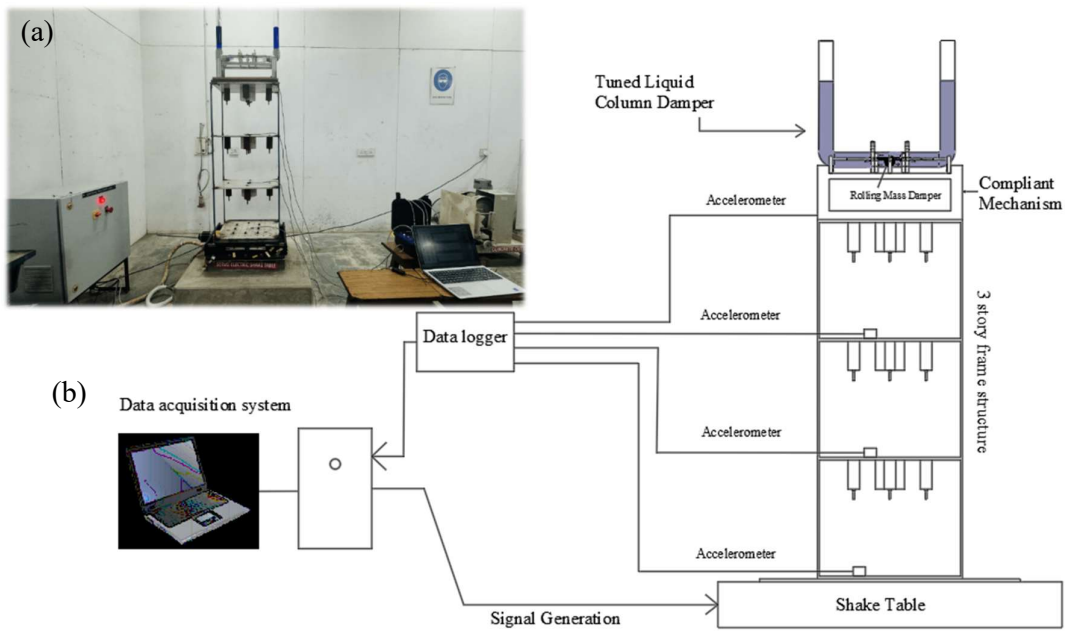


Figure 3.6: a) Experimental set up of various components of the shake table setup and b) A flow chart illustrating the various components of the shake table.

A schematic representation of the setup in the laboratory is illustrates in Figure 3.8 (b). It is an experimental setup designed to study the vibration control performance of a Tuned Liquid Column Damper (TLCD) with a compliant mechanism mounted on a three-story frame structure. The structure is placed on a shake table that simulates ground motion, to generate earthquakes vibration. At the top of the frame, the TLCD, consists of a U-shaped tube partially filled with liquid is installed to mitigate vibrations through the oscillatory movement of the fluid. A compliant mechanism is integrated to enhance the system's flexibility and energy dissipation capabilities. Accelerometers are strategically placed on each floor of the frame to capture the dynamic response of the structure during seismic testing. These sensors feed real-time data into a data logger, which transmits the information to a data acquisition system for

monitoring and analysis. The shake table is controlled through a signal generation system that sends predefined or scaled seismic inputs to replicate realistic loading conditions. This comprehensive setup enables the detailed evaluation of how the TLCD system affects structural behavior under dynamic excitation, particularly focusing on vibration reduction and improved stability in short-period structures.

### **3.6. Summary**

This chapter discusses a novel Compliant Tuned Liquid Column Damper (CTLCD) developed for short-period structures, incorporating a compliant U-tube, partially filled with water, and a freely moving steel ball to enhance seismic vibration control. The system leverages fluid-structure interaction, impact damping from the ball, and flexibility from a compliant mechanism (using SMA springs), enabling effective energy dissipation and self-centering behavior. A three-story steel frame model (natural period  $\sim 0.3$ s) was fabricated using mild steel to replicate the dynamic behavior of a low-rise structure. Concentrated masses were added to meet a total structural mass of 100 kg. The TLCD used a 40 mm diameter acrylic tube with a 31.75 mm steel ball (ball-to-tube ratio = 0.8) to introduce fluid resistance through impact and turbulence. The compliant mechanism was constructed using 3D-printed components and Shape Memory Alloy (SMA) springs ( $k = 213.82$  N/m), which enhanced the system's restoring capacity and reduced residual displacements. A shake table test was conducted using 43 scaled ground motions (PGA  $\sim 0.5$ g, duration  $\leq 60$ s), selected and scaled from the PEER database. Ground motions were analyzed based on parameters such as PGA, PGD, RMS acceleration, and response spectra to evaluate structural response. The CTLCD with ball showed significant improvement in reducing displacement, acceleration, and vibration duration, especially for high-frequency excitations affecting short-period structures. This hybrid damping system offers a promising, maintenance-free solution for seismic protection of low-rise buildings, integrating fluid damping, mass impact, and compliant elasticity to enhance resilience against earthquakes.

The experimental results, based on data obtained from accelerometers installed on each floor of the model structure, will be discussed in Chapter 4. Measurements were recorded for all 43 ground motion inputs to evaluate the structural response. From this data, acceleration, displacement, and other dynamic response parameters were extracted using SeismoSignal. These results were then used to assess the effectiveness of the CTLCD in mitigating seismic vibrations.

### RESULTS AND DISCUSSIONS

#### 4.1. Overview

The experimental results were analyzed based on data collected from accelerometers installed on each floor of the model structure. Measurements were taken for 43 different ground motion records to evaluate the structural response. From this experimental data, acceleration, velocity, displacement, and other dynamic response parameters were extracted using SeismoSignal. These results were then used to assess the effectiveness of the proposed damper system, the compliant Tuned Liquid Column Damper (CTLCD), in mitigating seismic vibrations.

#### 4.2. Performance of the Uncontrol Building (without damper)

Seismic excitation of the building model was performed using a shake table by applying each of the 43 selected ground motions without the CTLCD. At each story level, acceleration and displacement time histories were measured and plotted to visualize the dynamic behavior of the structure. Additionally, the Root Mean Square (RMS) values were computed for each response parameter to provide an average measure of motion intensity.

The peak acceleration response increases with elevation, showing the influence of dynamic amplification effects, as observed in Figure 4.1. GM22 produced the highest peak values, marking it as the most critical case among the motions considered. Specifically, the peak acceleration at the third story reached 1.89 g, followed by 1.42 g at the second story and 1.12 g at the first story. This corresponds to a 24.9% reduction from the third to the second story, and a further 21.1% reduction from the second to the first story. Overall, the first story experienced a 40.7% lower peak acceleration than the third story. The RMS acceleration response, provides insight into the sustained energy input to the structure over time for various ground motions. Similar to the peak acceleration trends, GM22, 0.23 consistently results in the highest RMS acceleration across all three stories, indicating its dominance not only in peak intensity but also in prolonged shaking. The values generally decrease from the 3rd to the 1st story, reflecting the vertical attenuation of motion as it travels downward through the structure. This reduction suggests that upper stories experience more continuous excitation, which is

typical in flexible multi-story buildings. Ground motions such as GM23 and GM17 also exhibit relatively high RMS acceleration, identifying them as significant in terms of sustained seismic input. Overall, the RMS acceleration profile highlights that upper stories are more susceptible to prolonged dynamic effects, reinforcing the importance of considering both peak and cumulative energy measures in structural response assessments.

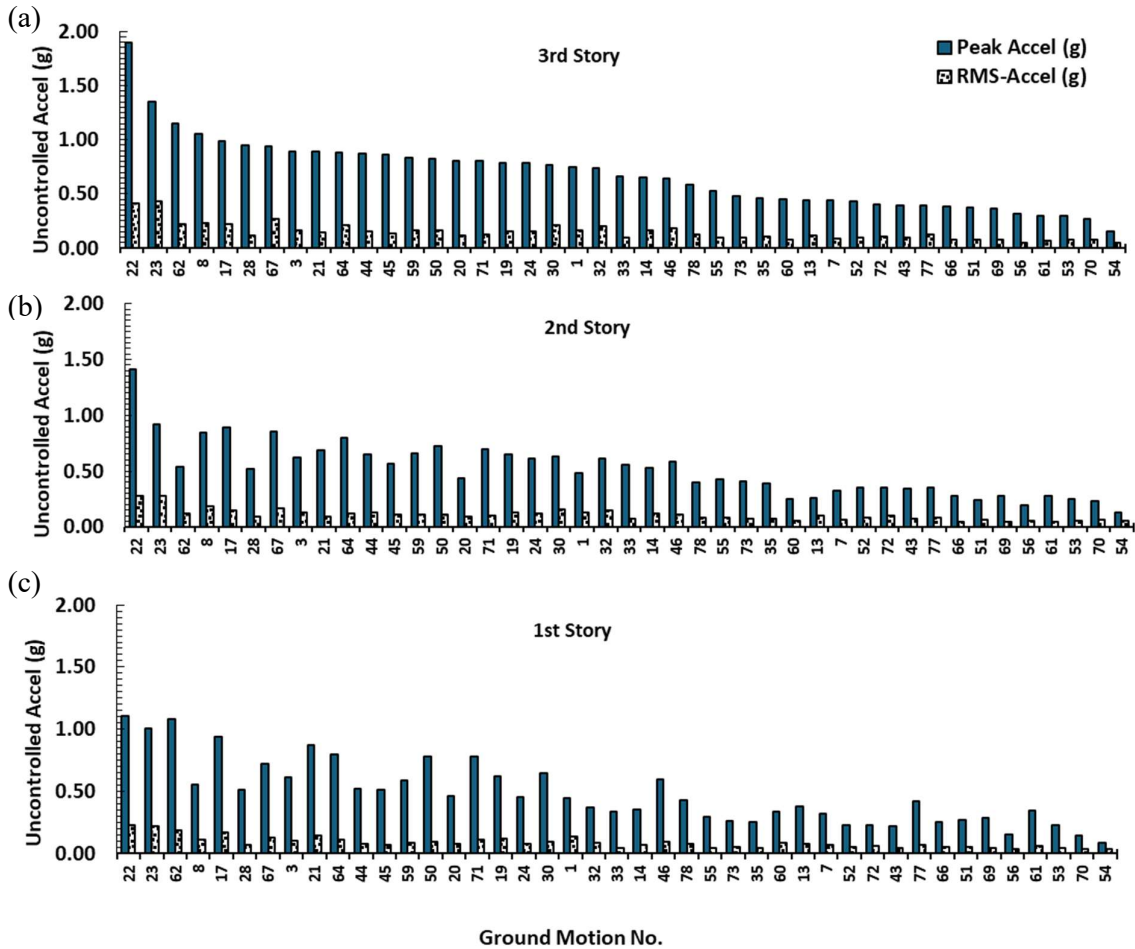


Figure 4.1: Peak and RMS uncontrolled acceleration response on (a) 3<sup>rd</sup> story, (b) 2<sup>nd</sup> story and (c) 1<sup>st</sup> story under 43 different ground motions.

The displacement response of the building model was analyzed for all 43 ground motions to capture the structural deformations experienced during seismic excitation, as shown in Figure 4.2. Displacement provides direct insight into structural drift and the potential for damage or serviceability issues. In addition to peak displacement, RMS displacement values were calculated to assess sustained structural deformation over time. Figure 4.2 reveals that displacement values are highest at the third story, with relatively minor differences between the first and second stories, indicating prolonged lateral movement in the upper floors an important factor in evaluating inter-story drift and overall seismic performance. Displacement

time histories were analyzed and plotted at each story level to visualize the extent and progression of lateral movement throughout the structure. Among the 43 records, Ground Motion 17 produced the maximum peak displacement, making it the most critical in terms of structural deformation. The third story experienced a peak displacement of 0.110 m, followed by 0.028 m at the second story and 0.045 m at the first story. This corresponds to a 74.5% reduction from the third to the second story, and a 60.7% increase from the second to the first story, indicating an irregular distribution of displacement across the building height. Ground Motion Nos. 17, 46, and 1 consistently produced the highest peak and RMS displacements across all stories, while the remaining ground motions exhibited significantly lower responses. Overall, peak displacement represents the maximum instantaneous response, while RMS displacement reflects the average energy content over time both of which are crucial for assessing the structural vulnerability of an uncontrolled system.

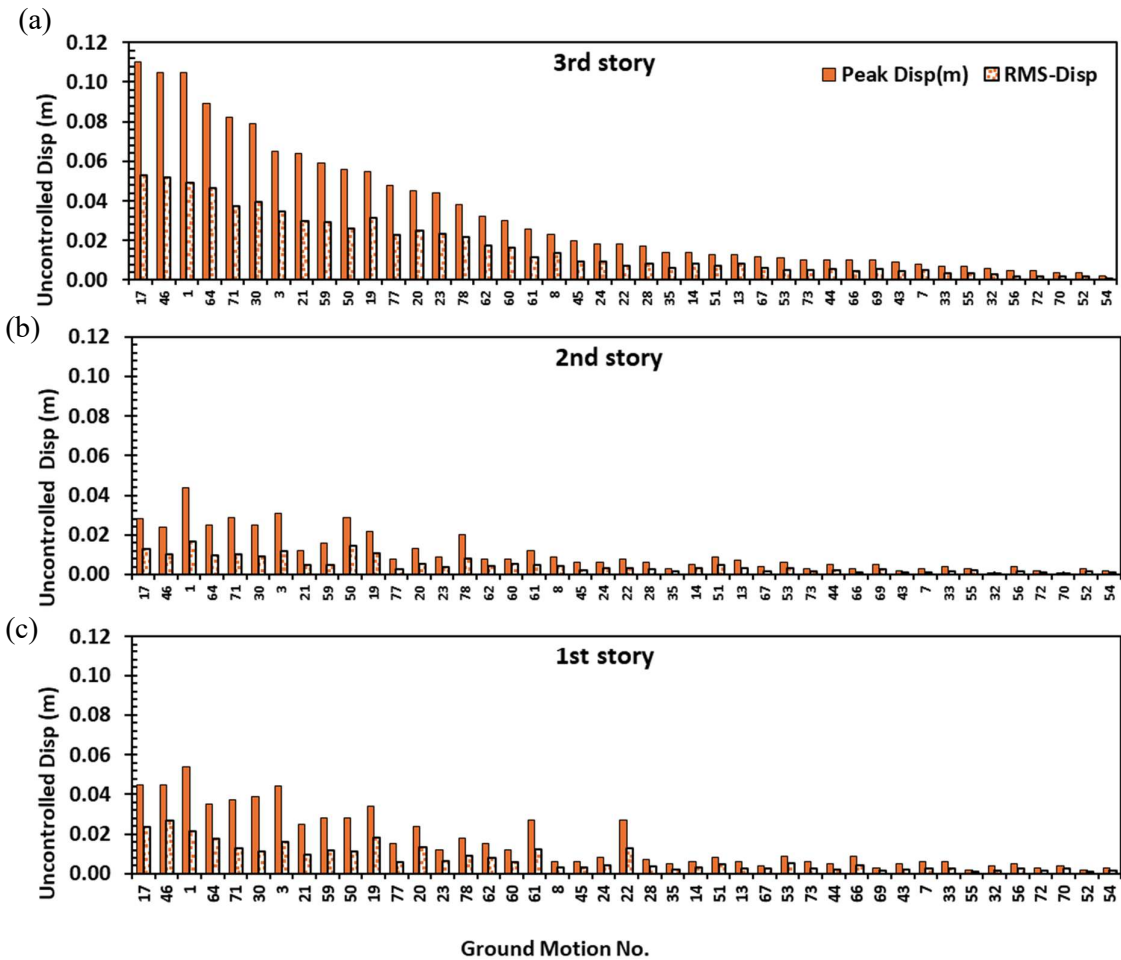


Figure 4.2: Peak and RMS uncontrolled displacement response on (a) 3<sup>rd</sup> story, (b) 2<sup>nd</sup> story and (c) 1<sup>st</sup> story under 43 different ground motions.

### 4.3. Performance of the Building with CTLCD

The Compliant Tuned Liquid Column Damper (CTLCD) was installed at the top of the scaled structure, and a detailed study of acceleration and displacement responses was conducted using the same 43 ground motions. Graphs were plotted based on the peak responses of the uncontrolled structure, where GM22 produced the highest peak acceleration, and GM14 produced the highest peak displacement. The ground motions were arranged in descending order of peak acceleration and displacement observed in the uncontrolled case for consistent comparison.

The controlled performance shows some variations from the uncontrolled performance across different motions as seen in Figure 4.3, the overall reduction in structural response due to the CTLCD was significant and effective. As seen in the uncontrolled structure, the peak response of acceleration was observed to be maximum at higher story followed by the lower stories, same have been observed in the controlled structure. As seen in Figure 4.3, GM22 produced the highest peak acceleration across all three stories, with the third story reaching approximately 1.30g, followed by GM23, GM62, and GM59. This suggests that despite the presence of a control mechanism, certain strong excitations still induce significant peak accelerations, particularly at the upper levels.

As observed in the displacement responses, the third story consistently experiences the highest accelerations, both in peak and RMS terms, followed by the second and first stories. This vertical distribution is characteristic of flexible structures, where upper stories are more susceptible to amplified dynamic effects due to their larger sway and higher mode participation. The acceleration values gradually decrease from top to bottom, reaffirming the typical top-heavy response pattern in multi-story frames. When comparing peak and RMS acceleration trends, it is evident that while the peak values provide insight into the extreme forces acting momentarily on the structure, RMS acceleration gives a clearer view of the sustained dynamic demand imposed during an earthquake.

The RMS acceleration values are significantly lower than the peak values typically remaining below 0.4g, but still provide crucial insight into the average vibrational intensity. Motions such as GM22, GM23, GM62, and GM59 also resulted in the highest RMS acceleration values across all stories. These findings confirm that while the control system may not eliminate all peak responses, it contributes to a considerable reduction in the energy transmitted to the structure. As such, both peak and RMS acceleration responses must be

evaluated to comprehensively assess the seismic performance of the structure under controlled conditions.

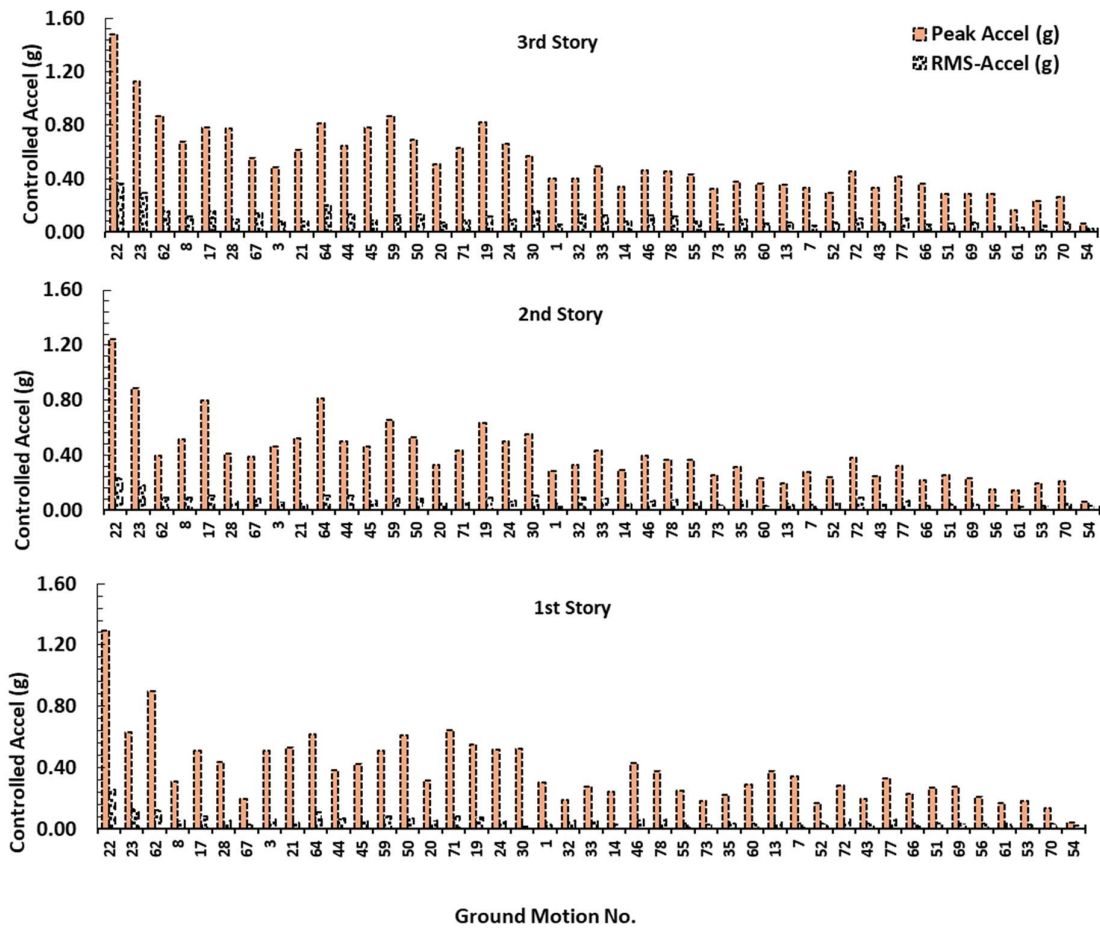


Figure 4.3: Peak and RMS acceleration response with CTLCD on (a) 3<sup>rd</sup> story, (b) 2<sup>nd</sup> story and (c) 1<sup>st</sup> story under 43 different grounds.

The controlled displacement response of the three-story building model, equipped with a vibration control device, was evaluated under all 43 ground motions, as presented in Figure 4.4. The results are presented in terms of peak displacement and root mean square (RMS) displacement at each story level. Among the recorded motions, Ground Motion 30 produced the highest peak displacement at the third story, reaching approximately 0.21 meters, followed by GM17, GM01, and GM03. This suggests that while the control system is generally effective, certain strong excitations still induce significant peak responses. Notably, the third story consistently exhibits the highest peak displacements across many ground motions, a trend that reflects the common dynamic behavior of flexible multi-story structures. This occurs due to amplification effects at higher elevations, often influenced by resonance and mode shape characteristics. The second and first stories show similar patterns but with comparatively lower

peak values, indicating a gradual reduction in displacement from top to bottom. This top-to-bottom gradient is characteristic of multi-story buildings, where upper floors are more susceptible to amplified motion under seismic loading.

When compared to the uncontrolled case, a substantial reduction in RMS displacement is observed across all stories, confirming the effectiveness of the control system in mitigating sustained vibrational responses during seismic excitation. However, for a few ground motions, the peak displacements in the controlled case slightly exceed those in the uncontrolled scenario. This suggests that while the device efficiently limits the average structural motion, it may not fully suppress extreme instantaneous responses under certain excitations. This observation highlights the need to assess both peak and RMS displacements to obtain a thorough evaluation of the control system's effectiveness. RMS displacement, as shown in Figure 4.4, provides a valuable complementary perspective by capturing the average displacement sustained throughout the duration of the seismic motion, thereby reflecting the energy content and prolonged dynamic behavior of the structure.

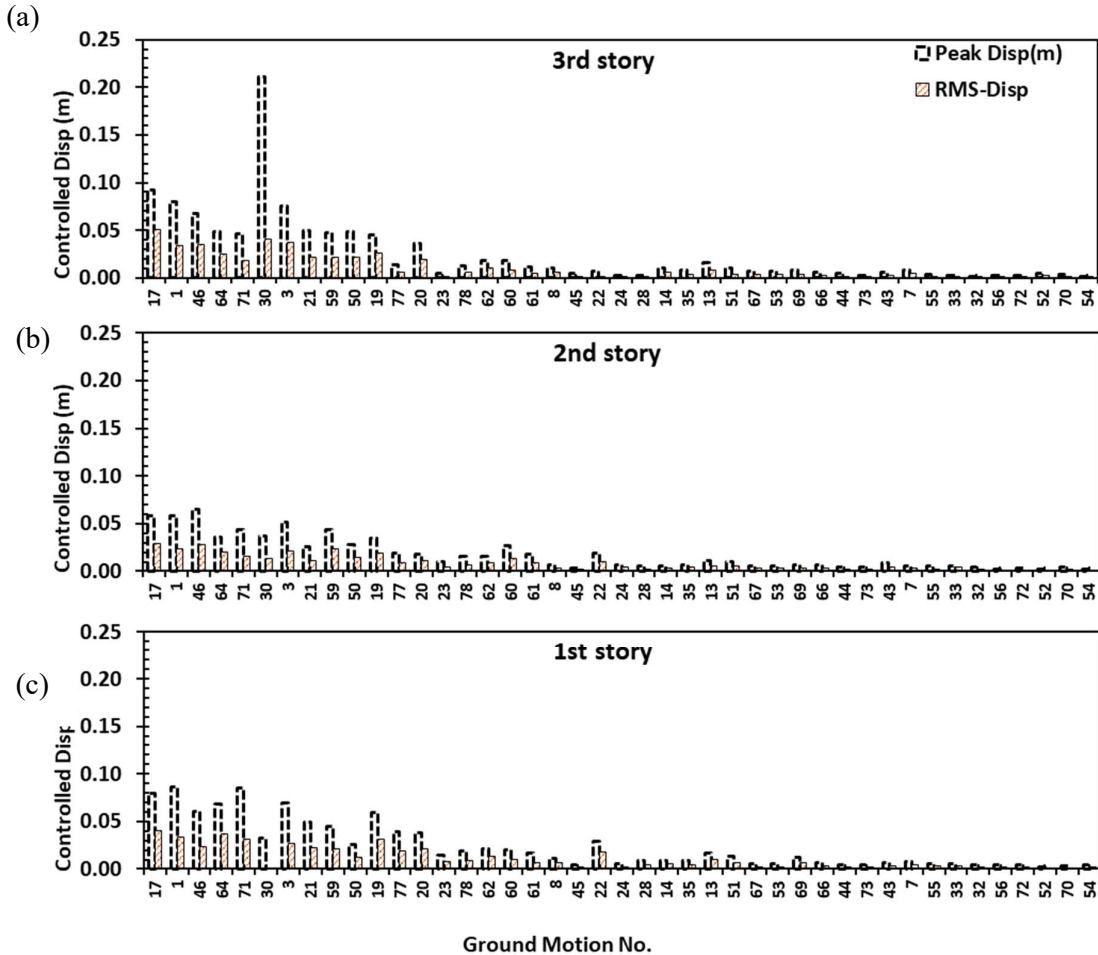


Figure 4.4: Peak and RMS displacement response with CTLCD on (a) 3<sup>rd</sup> story, (b) 2<sup>nd</sup> story and (c) 1<sup>st</sup> story under 43 different ground motions.

Ground motions such as GM01, GM03, GM17, and GM46 produced the highest RMS displacements across all floors. Although these RMS values remain significantly lower than peak displacements typically peaking around 0.02 meters, they offer critical insights into the intensity and duration of structural vibrations. Consistent with the peak displacement trend, the third story exhibits the highest RMS values, reaffirming the increased vulnerability of upper stories to prolonged lateral motion.

#### 4.4. Comparative Assessment of Parameters

To better understand the relationship between instantaneous and sustained seismic responses, scatter plots of RMS acceleration versus peak acceleration are presented for all three stories under both uncontrolled (UC) and controlled (C) conditions has been illustrated in Figure 4.5. These plots illustrate how well peak acceleration correlates with the energy sustained in the structure over time (RMS acceleration), using linear regression lines with associated equations and  $R^2$  values. The results reveal a strong positive linear correlation across all cases, with  $R^2$  values consistently above 0.92, indicating that peak acceleration is a good predictor of RMS response. In the uncontrolled (UC) condition, the slope of the linear fit between RMS and peak acceleration gradually decreases from the 3rd to the 1st story: 0.2169 (3rd), 0.1974 (2nd), and 0.1776 (1st). This indicates that the top floor experiences relatively more sustained acceleration for a given peak than the lower floors, likely due to modal amplification effects. When the CTLCD (C) is introduced, the slopes reduce across all stories: 0.2 (3rd), 0.1678 (2nd), and 0.1514 (1st), signifying a damping effect in both upper and lower stories. The percentage reduction in the slope from uncontrolled to controlled cases is 7.8% at the 3rd story, 15.0% at the 2nd story, and 14.8% at the 1st story. Notably, the middle and lower floors benefit the most, indicating that the damper is particularly effective in reducing sustained acceleration energy at these levels.

To evaluate the performance of damping devices such as the Compliant Tuned Liquid Column Damper (CTLCD). Control efficiency offers a quantitative assessment of how effectively a damper mitigates structural responses such as acceleration, displacement, and inter-story drift during seismic excitation. By comparing the dynamic behavior of the structure with and without the damper, the improvement in performance can be evaluated. To ensure a comprehensive evaluation of the CTLCD's effectiveness, a total of 43 ground motion records were analyzed. These records include both near-field and far-field events to capture the diverse dynamic demands that structures may encounter during real earthquake scenarios. Each ground

motion was applied to the experimental or numerical model, and the corresponding acceleration data was recorded using floor-level accelerometers. This multi-record analysis provides a statistically meaningful evaluation of the control efficiency and reliability of the CTLCD across a broad spectrum of seismic excitations.

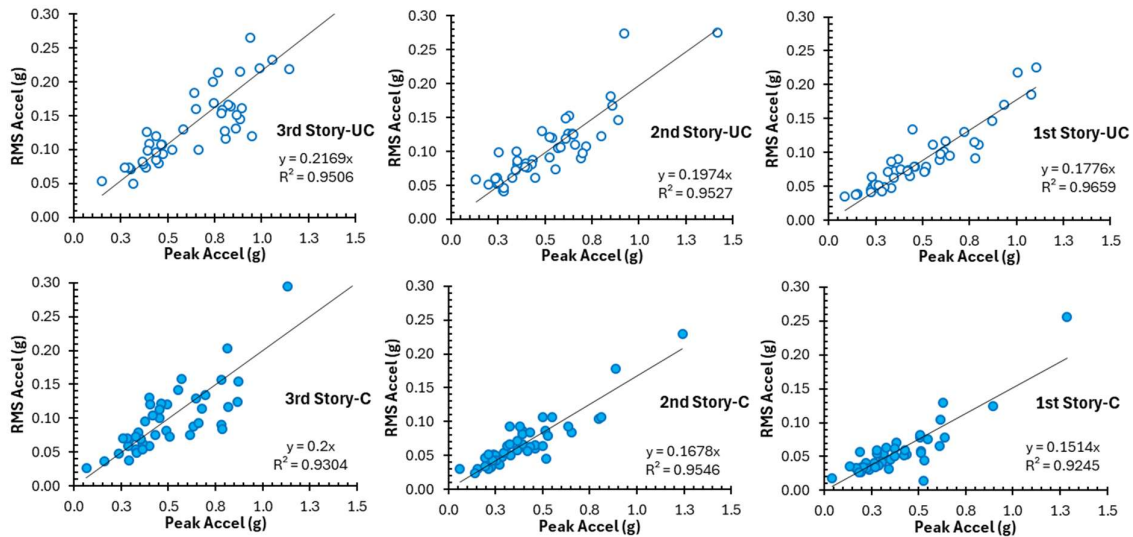


Figure 4.5: Scatter plots comparing RMS acceleration and peak acceleration for each story level in both the uncontrolled (UC) and controlled (C) cases.

The control efficiency of the Compliant Tuned Liquid Column Damper (CTLCD) was evaluated across the first, second, and third stories of the structure under 43 distinct ground motion records. As illustrated in the Figure 4.6, the CTLCD demonstrated varying levels of effectiveness depending on the story level and the specific ground motion. Overall, higher control efficiencies were observed in terms of both peak acceleration and RMS acceleration, with values reaching up to approximately 70% in certain cases particularly at the first story. The trend shows that the damper consistently reduces RMS acceleration more effectively than peak acceleration across all floors, indicating its greater performance in mitigating sustained vibration energy rather than extreme instantaneous responses. Moreover, the damper's influence appears to diminish slightly at higher floors, which is expected due to the energy dissipation mechanism being more dominant near the damper installation level. The variability in efficiency across different ground motions also highlights the importance of accounting for a wide range of seismic inputs when evaluating damper performance. These results confirm the CTLCD's potential for improving structural seismic resilience, especially in short-period buildings.

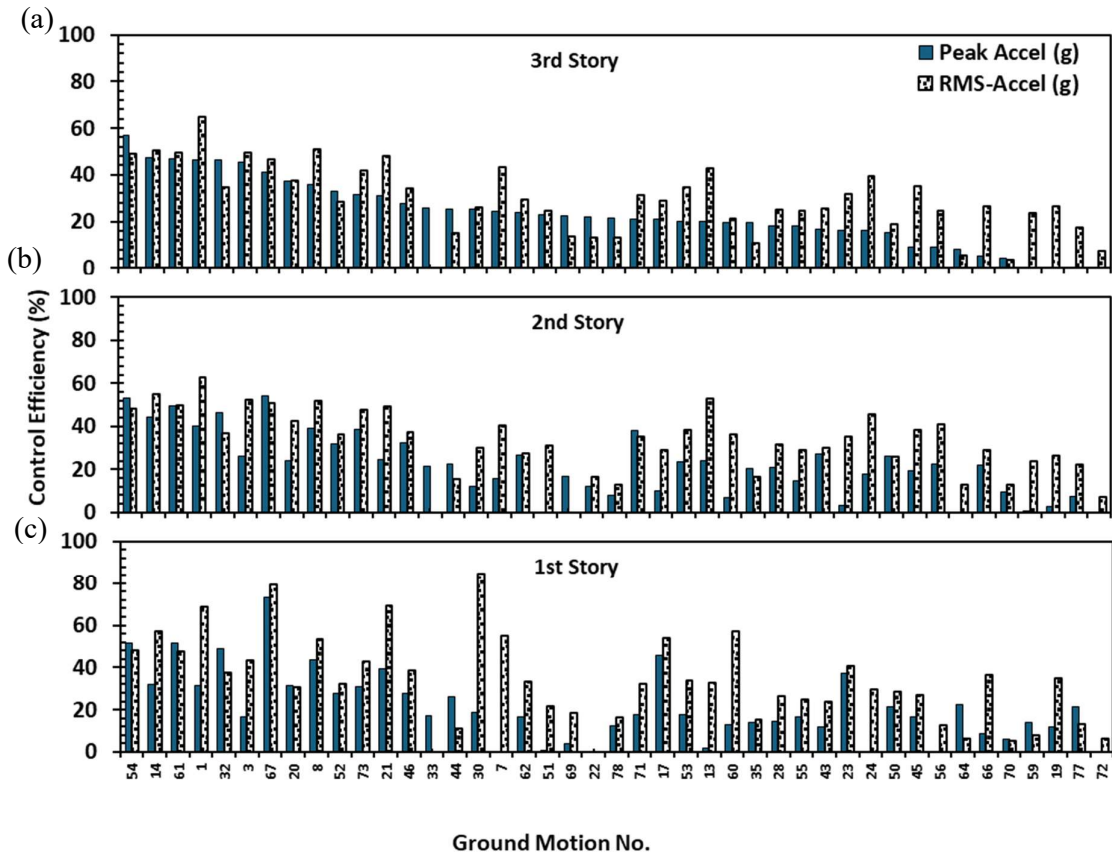


Figure 4.6: Control efficiency (%) in the acceleration response (peak and rms) of the CTLCD assisted building subjected to multiple ground motions (a) 3<sup>rd</sup> story, (b) 2<sup>nd</sup> story and (c) 1<sup>st</sup> story.

To complement the control efficiency analysis based on acceleration responses, the relationship between peak and RMS displacement was also studied for both uncontrolled (UC) and controlled (C) cases across all three stories. As shown in Figure 4.7, the scatter plots reveal a strong linear correlation between peak and RMS displacements in the uncontrolled condition, with high coefficients of determination ( $R^2 > 0.97$ ), indicating consistent displacement patterns across different ground motions. In the controlled case, while the linear trend remains, a noticeable reduction in both the slope and  $R^2$  values especially at the third story ( $R^2 = 0.8321$ ) suggests that the CTLCD introduces nonlinear damping effects that disrupt the proportionality between peak and RMS responses. This observation aligns with the previous acceleration-based control efficiency results, where greater reductions were observed in RMS acceleration compared to peak acceleration. The consistent lowering of RMS displacement in the controlled state further confirms the damper's ability to attenuate sustained vibrations more effectively than transient peaks. Collectively, these results demonstrate that the CTLCD is particularly effective in reducing the energy content of a structure's dynamic response, making it well-

suiting for mitigating the damaging effects of long-duration and low-frequency seismic excitations.

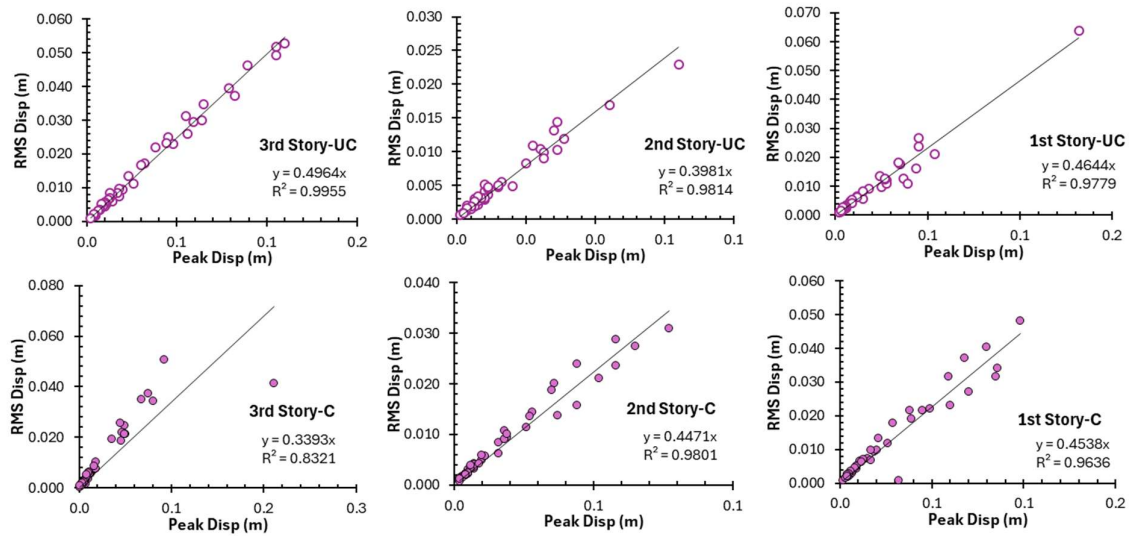


Figure 4.7: Scatter plots comparing RMS displacement and peak displacement for each story level in both the uncontrolled (UC) and controlled (C) cases.

Further analysis was conducted to evaluate the control efficiency in terms of peak displacement and RMS displacement, providing additional insight into the CTLCD's ability to reduce overall deformation demands. As shown in the Figure 4.8, the third story exhibits the highest displacement control efficiency across a wide range of ground motions, with several instances exceeding 80% reduction in both peak and RMS displacements. This aligns with the earlier scatter plot results, where the CTLCD significantly altered the displacement response characteristics. In contrast, the control efficiency at the first and second stories is comparatively lower, with effective control observed only under specific ground motions. This disparity suggests that the CTLCD's influence is more dominant at higher elevations where the damper-induced fluid motion and inertia effects are more pronounced. Additionally, a general trend of greater RMS displacement reduction over peak displacement can be observed, reinforcing the damper's role in mitigating cumulative motion rather than limiting transient peaks. These displacement-based results, combined with the acceleration and correlation analyses, confirm that the CTLCD contributes meaningfully to controlling both energy dissipation and deformation across the structure, particularly at the upper levels.

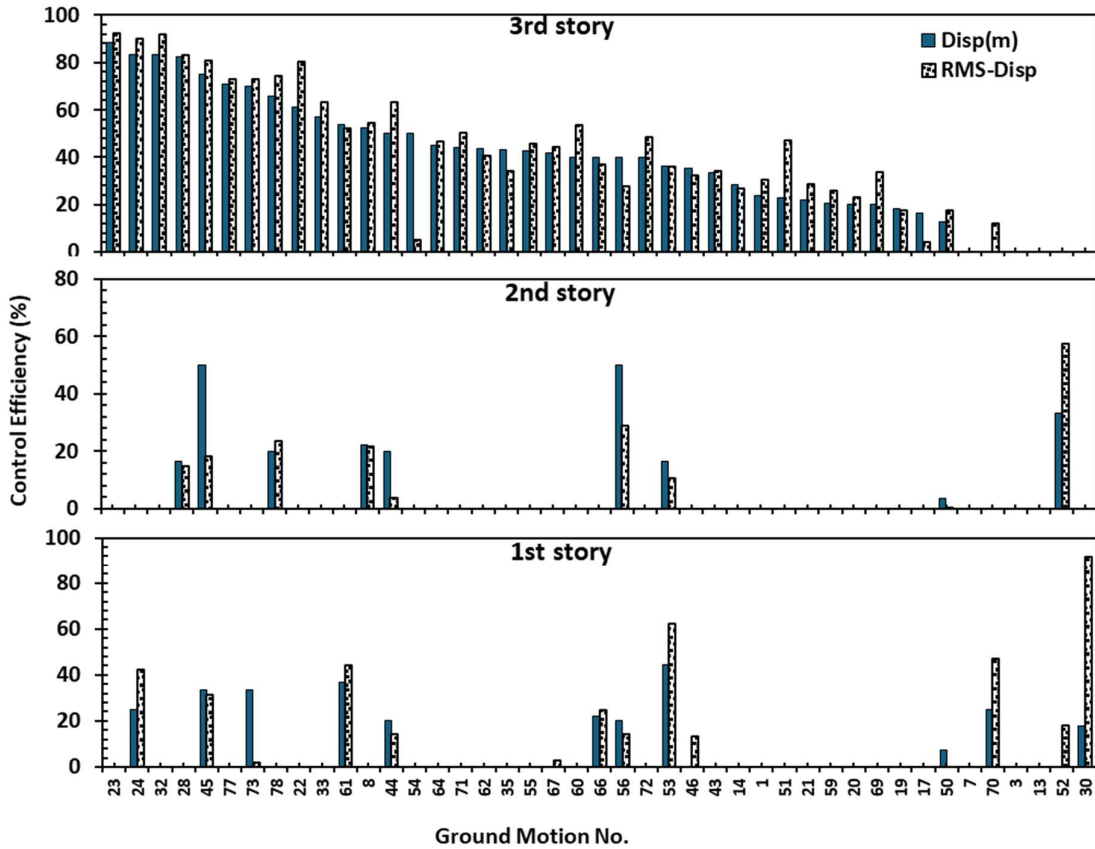


Figure 4.8: Control efficiency (%) in the displacement response (peak and rms) of the CTLCD assisted building subjected to multiple ground motions (a) 3<sup>rd</sup> story, (b) 2<sup>nd</sup> story and (c) 1<sup>st</sup> story

The acceleration response of the structure under 43 ground motions was analyzed to assess the effectiveness of the control system. Figure 4.9(a) presents the variation of peak acceleration along the height of the structure for both uncontrolled (UC) and controlled (C) cases. In the uncontrolled condition, the acceleration profiles (gray lines) show significant variation and higher peak values across the stories. However, in the controlled case (green lines), the acceleration values are consistently lower, especially at the upper stories. The red dashed lines representing the average response clearly indicate that the control system significantly reduces peak accelerations, with the effect being more prominent at higher stories. This observation is further supported by Figure 4.9 (b), which compares the average peak accelerations and standard deviations for both cases. In the uncontrolled scenario, the peak accelerations are recorded as 0.48 g, 0.52 g, and 0.68 g at the first, second, and third stories, respectively. After implementing the control system, these values are reduced to 0.38 g, 0.41 g, and 0.52 g, indicating a consistent and notable reduction in seismic demand across all levels. The standard deviation bars further suggest improved uniformity in the controlled responses, especially at higher stories. This performance is further substantiated in Figure 4.9 (c), which

illustrates the control efficiency in acceleration at each story level. The system achieves a 21.4% reduction at the first story, 21.35% at the second story, and 22.75% at the third story, clearly demonstrating a slight increase in control effectiveness with height. This trend emphasizes the control system's capability to counteract the amplified acceleration demands experienced in upper stories during seismic events, thereby enhancing overall structural safety and performance. This behavior can be attributed to the dynamic characteristics of multi-story structures, where higher stories tend to experience greater acceleration amplifications due to flexible mode shapes and increased displacement demands during seismic events. The control device, often tuned to target such dominant modes, becomes more effective in mitigating vibrations at these upper levels. Therefore, the increasing trend in control efficiency with height indicates that the implemented damping system is successfully suppressing acceleration responses more significantly where they are most critical at the upper stories, enhancing structural safety and performance during seismic loading.

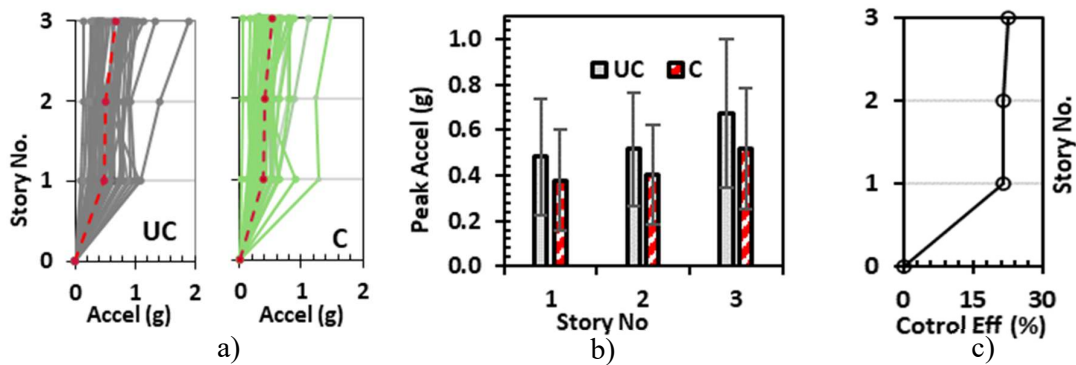


Figure 4.9: Comparative peak acceleration values obtained for – (a) all ground motions, (b) average and standard deviations from all the GMs, (c) control efficiency (%) obtained.

The comparison of displacement responses across the structure provides further insight into the control system's effectiveness. The first plot Figure 4.10 (a), illustrates the inter-story displacement profiles for both uncontrolled (UC) and controlled (C) cases. The red dashed line represents the median response across the suite of ground motions. In the UC case, wider spreads and higher peak displacements are observed across all stories, whereas the C case shows a more concentrated and reduced profile, indicating that the control device effectively minimizes lateral movement. The second Figure 4.10 (b), compares the mean peak displacement at each story for UC (grey bars) and C (red hatched bars) cases, along with standard deviation bars. At the first story, the mean displacement increases from 0.0184 m (UC) to 0.025 m (C); similarly, at the second story, it rises from 0.012 m (UC) to 0.0187 m (C). However, at the third story, displacement is effectively reduced from 0.033 m (UC) to

0.022 m (C). These values indicate that while the control strategy increases displacement at the lower stories, it significantly suppresses displacement at the top level. The standard deviation bars further show that variability is also reduced at the third story, supporting the view that the control mechanism is more effective at higher elevations. The Figure 4.10 (c), depicts the control efficiency (%) in displacement at each story, further quantifies the effectiveness of the damping system. Interestingly, the control efficiency is not uniformly positive across the structure. While the third story shows a significant improvement with a control efficiency of 33.62%, the first and second stories exhibit negative control efficiencies of  $-35.46\%$  and  $-55.74\%$ , respectively. This indicates that the control system inadvertently increased displacements at the lower stories, a phenomenon potentially attributed to control spillover or energy redistribution effects. Such outcomes are not uncommon in tuned control systems and underscore the importance of optimized tuning to balance performance across all floors. Nevertheless, the overall trend remains favourable at higher elevations, reaffirming the damper's effectiveness in reducing peak displacement at the upper levels.

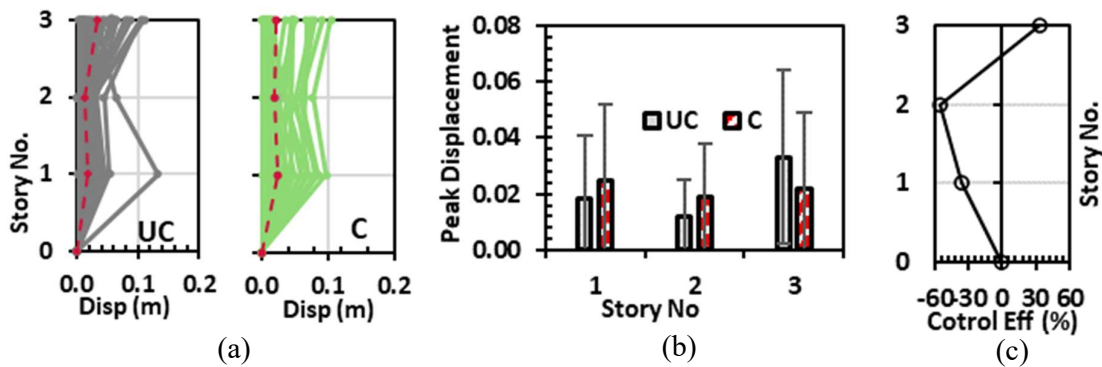


Figure 4.10: Comparative peak displacement values obtained for – (a) all ground motions, (b) average and standard deviations from all the GMs, (c) control efficiency (%) obtained.

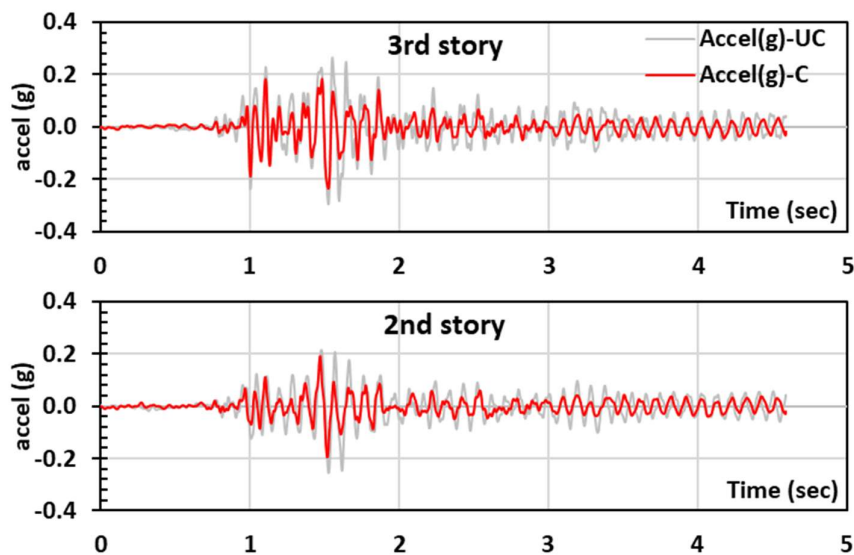
These findings suggest that the CTLCD not only reduces the magnitude of seismic acceleration but also controls inter-story displacements effectively, particularly at upper levels where dynamic amplification is more pronounced. The system thereby enhances the structural resilience and occupant safety during seismic events. The combination of reduced acceleration and displacement confirms that the CTLCD is a viable and efficient passive control device for vibration mitigation in multi-story structures subjected to ground motions.

#### 4.5. Story-wise Response

To gain deeper insight into the influence of the control system on the dynamic responses at various story levels, time-history comparisons of acceleration, velocity, and displacement

were conducted for each floor. The structural responses under both controlled and uncontrolled conditions were analyzed using data obtained from accelerometers and processed through SeismoSignal. These time history plots offer insight into the transient behavior of the structure during seismic events and illustrate the effectiveness of the CTLCD in real-time response reduction. By comparing the time-varying responses of each story individually, it becomes possible to assess not only the peak response mitigation but also the overall behavior across the duration of the ground motion.

The acceleration time histories at the 1st, 2nd, and 3rd stories are illustrated in Figures 4.11. The grey lines represent the response of the uncontrolled (UC) structure, while the red lines indicate the response of the controlled (C) structure with the damping device. At the 3rd story, a noticeable reduction in acceleration is observed in the controlled case, especially during the peak response period (around 0.7–1.2 seconds). At the 2nd story, the controlled response shows significant damping compared to the uncontrolled case, with visibly lower peak amplitude. At the 1st story, although both cases experience higher accelerations compared to the lower stories, the controlled structure again demonstrates improved damping with reduced amplitude and faster decay in oscillations. These time history plots visually confirm the role of the damping system in attenuating seismic accelerations at all story levels, particularly by reducing peak magnitudes and settling time. This is consistent with the peak acceleration values and control efficiency data presented earlier, where a reduction of approximately 21.4%, 21.35%, and 22.75% was achieved at the 1st, 2nd, and 3rd stories, respectively.



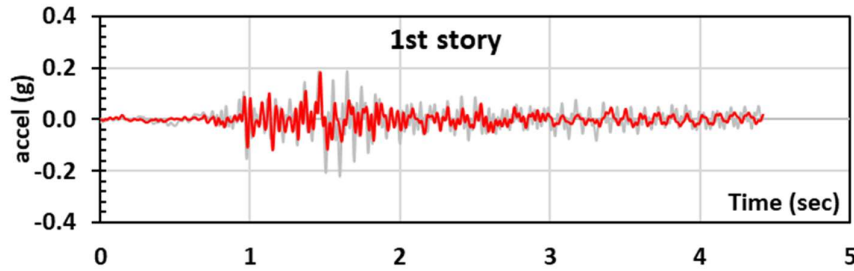
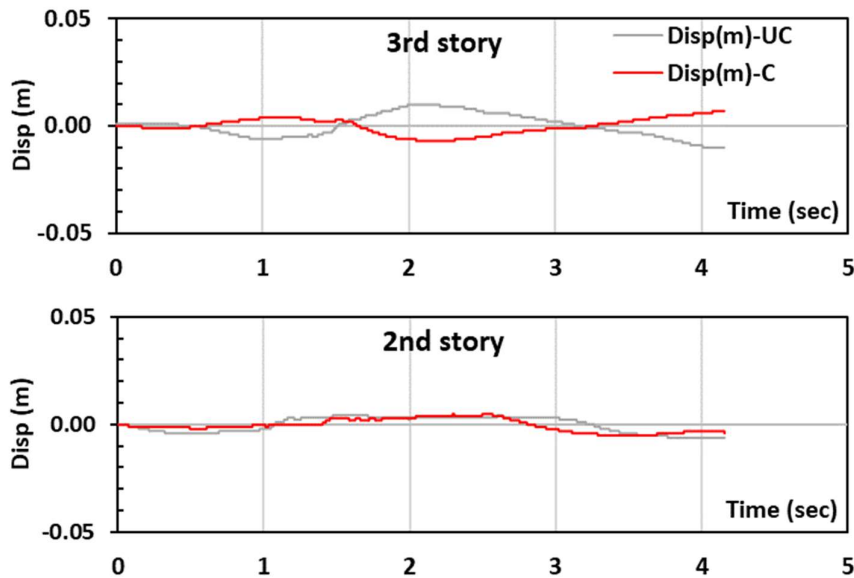


Figure 4.11: Story wise (top to bottom: 3<sup>rd</sup> to 1<sup>st</sup> floor) acceleration response time history for the GM 53.

The displacement response plots for the 1st, 2nd, and 3rd stories from Figure 4.12, illustrate the structural movement over time, comparing the uncontrolled (UC, grey line) and controlled (C, red line) cases. These graphs reveal different effects of the control strategy at each level of the structure. In the 3rd story, the uncontrolled displacement reaches a noticeable peak of over 0.005 m around 1.2 seconds, indicating significant lateral movement. The controlled displacement, however, remains extremely low and flat throughout the time history, suggesting that the control system is highly effective in suppressing displacement at this top level. In the 2nd story, the behavior is more nuanced. Both the controlled and uncontrolled responses show movement, but the controlled case exhibits higher displacements in certain intervals, especially between 1.0 and 2.0 seconds. This might suggest a redistribution of energy from the upper story or a control-induced response tailored to reduce overall structural damage rather than minimize displacement at every individual floor.



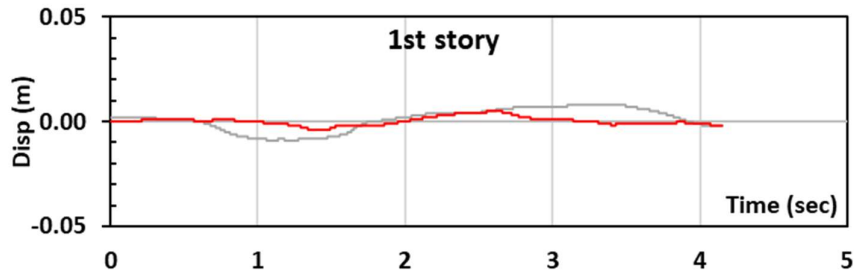


Figure 4.12: Story wise (top to bottom: 3<sup>rd</sup> to 1<sup>st</sup> floor) displacement response time history for the GM 53.

In the 1st story, the controlled and uncontrolled displacements follow a similar pattern, with the controlled response slightly exceeding the uncontrolled one in magnitude. This again may reflect the effect of energy dissipation or redistribution strategies that prioritize higher-story response reduction. Overall, these results indicate that while the control system is highly effective at minimizing displacement in the upper story (3rd), it allows or even slightly increases displacement in the lower stories (1st and 2nd). This is often acceptable in structural control design, as minimizing the relative motion and damage in the more vulnerable upper levels tends to be a higher priority.

#### 4.6. Summary

This chapter presented a detailed evaluation of the seismic performance of a three-story building model subjected to 43 different ground motion records, both without and with the implementation of a Compliant Tuned Liquid Column Damper (CTLCD). The study focused on analyzing acceleration and displacement responses using both peak and RMS metrics to assess structural behavior and the effectiveness of the CTLCD in reducing seismic demands.

In the absence of the control device, the structure exhibited increasing peak and RMS responses with height, demonstrating the influence of dynamic amplification, particularly at the third story. Ground motions such as GM22 and GM17 produced the most critical responses in terms of both acceleration and displacement. The upper story consistently experienced larger and more sustained motion, indicating higher vulnerability to seismic excitations due to modal amplification effects. RMS values, in particular, highlighted the intensity and duration of vibrations, providing insight beyond what peak responses alone could capture. After installing the CTLCD, a significant reduction in RMS acceleration and displacement was observed across all story levels, with the third story showing the greatest improvement. While peak responses were not uniformly decreased and, in some cases, slightly increased at the lower levels, the energy content of the vibrations was consistently reduced. Scatter plot analyses revealed strong

linear correlations between peak and RMS values in the uncontrolled case. These relationships became less consistent with the control system in place, especially at the third story, suggesting nonlinear damping effects introduced by the CTLCD.

The control efficiency evaluation showed the damper's ability to reduce seismic responses effectively, with the highest reduction rates recorded at the first and third stories. Peak and RMS acceleration reductions reached up to 70% under certain ground motions. Displacement-based control efficiency was also most prominent at the third story, where reductions exceeded 80% in some cases. At lower stories, control effectiveness was more variable, with a few instances of increased displacement due to energy redistribution—common in tuned mass systems. Time history analyses further supported these findings. At the third story, the CTLCD significantly dampened acceleration and displacement peaks and shortened vibration duration. The control system showed a more stable and reduced response pattern, particularly during critical time windows. At the lower stories, the device sometimes led to slight increases in displacement, a tradeoff accepted in favor of reducing damage at higher levels where motion is typically more severe.

This chapter demonstrates the capacity of the CTLCD to effectively reduce seismic demands in flexible multi-story structures. The reduction in both peak and sustained responses at critical locations reinforces the value of using compliant damping systems to enhance seismic performance, particularly at upper stories where the risk of damage is more pronounced.

### CONCLUSIONS AND FUTURE SCOPE

#### 5.1 Overview

This chapter presents a summary of the key findings and insights obtained from the experimental investigation into the seismic performance of a three-story building model equipped with a Compliant Tuned Liquid Column Damper (CTLCD). The conclusions are drawn based on the comparative analysis of acceleration and displacement responses under controlled and uncontrolled conditions using 43 different ground motions. In addition to highlighting the effectiveness of the CTLCD in mitigating structural vibrations, this chapter also outlines potential areas for future research and improvements in damper design and implementation for enhanced seismic performance in multi-story buildings.

#### 5.2 Conclusions

Based on the detailed experimental investigation and analysis presented in the preceding chapters, several significant conclusions can be drawn regarding the seismic performance of the three-story building model, both with and without the Compliant Tuned Liquid Column Damper (CTLCD). The comparative evaluation using 43 different ground motion records offers valuable insights into the structure's dynamic behavior and the effectiveness of the CTLCD as a passive control system. The key findings from this study are summarized below:

- The installation of the CTLCD led to significant reductions in both peak and RMS acceleration and displacement responses, especially at the upper stories where dynamic amplification is highest. Time history comparisons confirmed that the damper effectively reduced peak amplitudes and vibration duration, limiting excessive lateral displacements and potential inter-story drift damage.
- The CTLCD demonstrated higher efficiency in reducing RMS responses compared to peak values, indicating its superior ability to dissipate sustained vibrational energy rather than suppress instantaneous seismic shocks. Scatter plot analyses further showed that the introduction of the damper weakened the linear correlation between peak and RMS responses, highlighting its nonlinear damping behaviour.

- While the CTLCD substantially reduced accelerations and displacements at the third story (up to 34–40% reduction), slight increases in displacement were observed at lower stories, with the 2nd story showing RMS displacement increases of up to 88%. This redistribution is a known phenomenon in tuned damping systems and underscores the need for careful calibration to balance acceleration control with displacement management across all floors.
- The damper's performance varied with the characteristics of the input ground motion. Certain ground motions, such as GM22 and GM17, triggered higher structural responses and benefited most from control, indicating that the CTLCD's effectiveness is influenced by the frequency content and intensity of seismic events.
- Beyond reducing mean structural responses, the CTLCD also lowered the standard deviation of responses across multiple ground motions. This consistent reduction implies more uniform and predictable seismic performance, supporting its practical application in flexible multi-story structures when properly tuned and designed.

### 5.3 Future Scope

The present study has successfully demonstrated the efficiency of a Compliant Tuned Liquid Column Damper (CTLCD) in reducing seismic responses in a scaled three-story building model. However, there remain several avenues for further research and development to enhance the understanding and practical implementation of such damping systems. The following points outline the potential future scope:

- Further optimization of damper parameters such as orifice size, liquid column length, and ball mass can be undertaken using advanced computational techniques, including genetic algorithms and machine learning, to improve the tuning precision and dynamic performance of the CTLCD.
- Moreover, the ground motion dataset can be expanded to include a wider range of records, particularly near-fault earthquakes and long-duration events, to evaluate the CTLCD's effectiveness under more severe and complex seismic conditions.
- Future research may explore the combined use of CTLCDs with other passive or semi-active control devices, such as base isolation systems or tuned mass dampers, to enhance vibration control over a broader frequency range and improve the system's adaptability to varying seismic demands.

## ONGOING PUBLICATIONS

1. Nganthoibi, A.C, Choudhury, T., and Pandey, D. K (2025) “Review on the Use of Tuned Liquid Dampers for Vibration Control in Structures” In Proceedings of the 14th International Symposium on Plasticity and Impact Mechanics (IMPLAST 2025), Vol. 4: Structural Response to Dynamic Loads. (*In review*). Indian Institute of Technology Roorkee, Roorkee, India.
2. Nganthoibi, A. C., Choudhury, T., and Pandey, D. K. (2025). “Tuned Liquid Column Dampers (TLCD) For Seismic Vibration Attenuation: Research Trends and Recent Developments”. Manuscript under review, *In Structures* (Elsevier).
3. Nganthoibi, A. C., Pandey, D. K., and Choudhury, T. (2025). “Seismic Vibration Control for Low-Rise Buildings using Tuned Liquid Column Damper Based on a Novel Compliant Mechanism.” *Submitted to Journal of Building Engineering*.

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