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ABSTRACT

Passive Tuned Mass Dampers (TMDs) and their multiple-tuned configurations (MTMDs) are frequently utilized for controlling vibrations in multi-story framed structures. The issue is that the standard design methodology assumes that the structure will have a linear elastic behavior. When the RC structures are subjected to strong seismic motions, due to cracking, yielding or stiffness degradation can alter the dynamic characteristics of the structure and cause reduction in structures performance as well reduce effectiveness of various frequency-tuned devices

In the study we investigated the optimization methodology for a distributed 2-TMD system utilizing a nonlinear multistory Reinforced Concrete frame. For the analysis the structural response was simulated using the Open System for Earthquake Energy Simulation using the python 3.8 interface (OPENSEESPy), the framework accounts for steel degradation concrete crushing as axial-flexure interaction utilizing the fiber-section approach.

The mass ratio of the TMD and the spatial location of the TMD placement was investigated utilizing a parametric study. The mass ratio varied between 1% to 10% and the 2-TMD system was placed on each floor from first floor to the top floor on the roof. The study results concluded that the optimized mass ratio for the 2-TMD system is 6.0%, beyond which the efficiency starts to reduce with increase in mass ratio, and the optimum location for TMD placement was identified as the roof.

Sensitivity analysis for the structures damping ratio and tuning frequency with the mass ratio was conducted to find the optimum parameters of the 2-TMD system for maximum efficacy. To check for the effectiveness of the optimized damper configuration, it was simulated under eight different historical earth records. The simulations suggested that this proposed 2-TMD configuration is highly robust, with performance remaining relatively stable despite moderate detuning. Nonlinear time-history analyses across the eight earthquake suites further justified the efficacy of the TMD, displacement reductions ranging from 19.79% up to 68.27%. By preventing the structure from entering severe, irreversible yielding, this optimized system helps protect the structural load path and significantly reduces the overall likelihood of collapse.

⁴² CHAPTER 1 INTRODUCTION

1.1. BACKGROUND:

Since the dawn of civilization, natural disasters have been an integral part of life across the globe. These events have impacted all life form, be it humans, animals or vegetation. While some events have minimal impact, others are catastrophic, leading to considerable loss of life and property. Without proper mitigation and adequate precautionary measures, large-magnitude disasters can severely disrupt entire ecosystem and urban infrastructures. Among these natural hazards, earthquakes are widely regarded as one of the most fatal and destructive.

Earthquakes primarily occur whenever there is movement in tectonic plates. Which leads to evolution of tremendous energy in the form of seismic waves. The severity and destructiveness of an earthquake at a specific location are determined by its magnitude, focal depth, and distance from the epicenter. Globally, earthquake magnitude is historically measured using the Richard Scales (alongside the more modern Moment Magnitude scale), which ranges the magnitude of earthquakes between 0 to 9. The higher the number on the scale, the more the severity of an earthquake. Historical data indicates that any earthquake with magnitude greater than 7.0 is highly hazardous and capable of causing catastrophic loss of life and widespread structural collapse. The highest frequency of these seismic events occurs along the Pacific Ring of Fire, a highly active tectonic belt that spans across numerous countries, including Japan, Indonesia, Papua New Guinea and Guatemala. According to historical seismic records, most of the world's most devastating earthquakes have had their epicenter within the highly volatile region.

During recent years, the construction of tall buildings has surged globally. This rapid vertical expansion is driven not only by the need to accommodate dense urban population and conserve space but also by the desire to establish architectural landmarks and showcase technological advancement. Because modern design practices heavily utilize high-strength, lightweight materials, these increasingly slender structures exhibit

significant flexibility and low inherent structural damping. Consequently, they are highly susceptible to intense dynamic excitation, particularly from strong winds and earthquakes. While large lateral displacement may not always threaten the ultimate structural integrity of the building, excessive vibration can cause several discomforts to occupants and render the building unserviceable.

Therefore, engineers must implement measures to make earthquakes and damage resistant. It's not possible to make any structure immune, but we can make amends on our part, so this structure doesn't get too much damage, and we can save life and property. For this purpose, every country has their own standard codes for constructing building and materials properties. In, India, standards such as IS: 1893 and IS: 13920 dictate the fundamental criteria for earthquake-resistant design.

The inherent structural damping in large modern buildings generally varies between 2% to 5% of critical damping, the natural energy dissipation mechanism such as internal material friction and localized plastic deformation fails to fully absorb and dissipate the seismic input energy. This makes integrating and connecting supplemental mechanical damping devices an essential design practice for modern high-rise structures. As per law of energy conservation, reducing vibration energy is achieved by dissipating kinetic energy applied due to seismic load.

The techniques for structural control are categorized under four categories: active, passive, semi-active and hybrid control. The system works by altering rigidity, mass, damping, shape or by exerting counterforces to the structural system. Various methods for vibration control have been globally employed, and among the various methods, passive control devices are popular due to their reliability. For selection of a device various factors and criteria are considered like efficiency in controlling vibration, various physical constraints, cost of operation, weight of system, investment required, need of maintenance and integrity of system.

1.2. METHODS OF CONTROL

Various methods have been developed to resist the dynamic effects of wind and earthquake; the methods are placed under following 4 categories.

³⁰ 1.2.1. Active control

Active control system works on **an external power source** to supply the required corrective control force to the structure. The system works by combining a computer, sensors, and actuators. The sensors are used to continuously monitor the structural response and forward the information to computer, the computer then computes the opposition power required and the information is then forwarded to electro-hydraulic or electro-mechanical actuator to apply force on the structure, this counteracts the forces on the structures.

While having high control capabilities, active control systems are not being widely adopted in structures due to their continuous dependency on external power sources. Also, the amount of power required for a high-rise structure is exceptionally high. Moreover, intense control forces are required during windstorms or earthquakes that are likely to cause widespread power outages. This lack of reliability of active control systems during emergencies. Furthermore, proper placement of the sensors and design of a feedback system lies outside the civil engineering design practice, the risk of inducing structural instability due to improper design, error in control feedback or delay in system makes the active control system unfit for use in everyday utilization.

²⁴ 1.2.2. Semi-active control

Semi-active control systems operate in a similar fashion to **active control systems**, yet they don't require the massive amount of energy needed for active control. As there is no need to supply mechanical energy to the primary system. Semi-active system can also be said to be a controllable passive control system. These energy in these devices is generated by ²⁸**motion of the structure and cannot add energy to the structural system**. Some examples of these devices are variable stiffness damper and variable friction damper.

The main benefit of semi-active control system is that it requires very little power supply for performing the required power supply can be supplied from a battery backup in situation of power failure during seismic events. Thus, it is a very practical and reliable alternative to the active system can be seen formed. Despite advantages, the control system implementation is not without flaws. The primary drawback of this system is similar to active system that is it reliance on the sensors, computer feedback , so a signal noise or time delay can cause the computational process limiting effectiveness.

²⁹ 1.2.3. Hybrid control

Hybrid control system combines active, semi-active and passive control devices to achieve maximum performance gains. By combining various advantages from various systems, the hybrid control system provides a much superior seismic mitigation. A critical advantage of this active passive hybrid system is enhanced inherent safety. The passive TMD serves as a reliable mechanical backup, guaranteeing that the structure remains protected even if the active device suffers a powerful failure or mechanical malfunction during a severe seismic event. The hybrid system provides the effectiveness of an active system , and in situations of power shortage the passive component still offers a degree of protection. Example of a hybrid system is hybrid base isolation and hybrid mass damper.

1.2.4. Passive control

The widely accepted and utilized control system in the industry is used for structural vibration mitigation. The passive control system does not require an external power source for functioning as it functions by resisting the motion of primary structure by absorbing a part of response motion of the structure and dissipate it in nature by converting it in heat or by transferring the kinetic energy. Friction sliding and hysteretic yielding are common examples of vibration mitigation through heat conversion and ¹⁵ Tuned mass damper (TMD) and base isolation are examples of device which utilizes the kinetic energy transfer.

1.3. ¹³ Tuned mass dampers

The Fundamental ⁵ concept of the Tuned Mass Damper was originally pioneered by Fram in 1909, and its mathematical principles for mitigating dynamic responses were subsequently formalized ³ by Ormondroyd and Den Hartog in 1928. A classical TMD is a ⁴⁸ passive control device consisting of secondary auxiliary mass connected to the primary structure by properly tuned linear stiffness and viscous damping elements. During dynamic excitation, the device provides a frequency dependent inertial resisting force that effectively increases the equivalent ⁴ damping of primary structure. When the natural frequency of the TMDs is precisely calibrated to match a target modal frequency of the ¹ primary structure, the auxiliary mass resonates out of phase with the structural motion. This out of phase movement establishes a continuous control force that facilitates the transfer of excessive ¹ kinetic energy from main structure to secondary mass, where it is subsequently exhibited by the dashboard.

While the success of the TMD in mitigating wind excited vibration in high rise buildings is well established, extensive numerical and experimental studies have now validated their effectiveness for transient seismic response control. The robustness and efficiency of a TMD are intrinsically governed by its dynamic tuning characteristics, allowable physical stroke, and ³ the mass ratio, defined as the ratio of the damper mass generalized effective mass of the building in the controlled vibration mode. For traditional wind applications, the TMD mass typically ranges between 1% and 10% of the building's effective mass. However, modern seismic applications increasingly explore large mass ratios as massive dampers fundamentally flatten the frequency response basin and prevent severe performance drops caused by frequency detuning.

Despite their effectiveness, traditional single unit TMD are optimized for a narrow frequency bandwidth and are highly sensitive to initial parameter mistuning. To achieve more robust broadband response control, a Multiple Tune Mass Damper configuration is often adopted. An MTMD system consists of several discrete dampers placed in parallel

or distributed spatially, featuring a range of natural frequencies distributed around the primary structure's tuning frequency. For an equivalent total mass, a distributed MTMD system can significantly enhance the equivalent damping introduced to the primary system, actively suppress multimode vibrations, and diametrically diminish the structural system's sensitivity to parameters uncertainties, and post-yield frequency shifts.

1.4. PRACTICAL APPLICATION OF TUNED MASS DAMPERS

1.4.1. Citicorp Centre, New York

One of the earliest full-scale structural implementations of a Tuned Mass Dampers (TMDs) was in the 280-meter-tall Citicorp Centre building in New York City. Completed in 1977, ³⁷ the structure exhibits a fundamental period of 6.5 seconds and a structural damping of 1% along both principal axes. To mitigate wind-induced oscillations, a massive 400-ton concrete TMD was installed on the 63rd floor near its crown. At the time of its installation, the TMD was about 250 times larger than any damper existing at that time. Operating via a pneumatic spring that provides the requisite structural tuning stiffness and bearing a pressurized oil to minimize friction, the device achieved a mass ratio of roughly 2% relative to the first modal mass. This installation successfully increased the building's overall effective damping from 1% to 4% of critical damping, reducing the sway amplitude by a factor of two.

1.4.2. John Hancock Tower, Boston

To suppress wind-induced dynamic response, the 60-story, 244-meters-tall John Hancock Tower in Boston was retrofitted with two massive TMDs, each weighing approximately 300 tons (2700 kN) and constructed from lead and steel blocks. The twin damper configuration optimized to resist the fundamental sway and torsional modes of the structure.

1.4.3. CN Tower, Toronto

Due to the unique perspective of design the Canadian National Tower in Toronto, addition of TMD became necessary to suppress the dynamic effect of wind induced vibration of building in second and fourth modes at the 102 m tall steel antenna at the tower top. The first and third modes of antenna had identical characteristics as a well-damped concrete structure.

To effectively dissipate the kinetic energy, two 9-ton doughnut-shaped steel rings were installed at elevations corresponding to the peak modal displacement. The twin rings were mounted on a universal joint, allowing omnidirectional rotation to work as a tuned mass irrespective of the wind excitation trajectory. Energy dissipation was achieved via four hydraulically activated viscous dashpots provided per ring.

1.4.4. ³⁹ Chiba Port Tower, Japan

The Chiba Port Tower, a 125-meter-tall steel structure weighing 1950 tons with a rhombus shaped plane, holds the distinction of being Japan's first tower to be equipped with a TMD system. The structures fundamental periods are 2.25 seconds ¹ in X-direction and 2.70 seconds in Y-direction, with an inherent critical damping ratio of 0.5% for the fundamental mode, while higher-mode damping ratio were assumed to be proportional to frequencies. To safely elevate the damping ratios were assumed to be proportional to their frequencies. To safely elevate this damping capacity, a TMD system was implemented for both principal directions. Utilizing mass ratios of approximately 1/120 and 1/80 relative to their first modal mass ¹⁴ in the X and Y directions, respectively, the dampers were precisely tuned to periods of 2.24 seconds and 2.72 seconds and 2.72 seconds. The installation successfully increased the equivalent ² damping ratio of the fundamental mode to 15% significantly enhancing the tower's serviceability.

In Japan, viaduct TMDs were utilized for mitigating the vibrations being induced by the traffic on a two-story steel structure present under the expressway.

³² The world's third-tallest hotel Burj AL Arab has been equipped with total 11 TMDs at different locations to control vibrations being induced by wind.

1.5. Objectives of work

⁷ The main objective of this study is to analytically investigate and optimize control capabilities of Multiple Tuned Mass Dampers (MTMDs) placed in nonlinear multi-story reinforced concrete frames .

- I. ²⁶ To develop a comprehensive nonlinear finite element model of a representative RC multistory frame using the OPENSEes platform, incorporating realistic material nonlinearity, cracking behavior, and cyclic degradation through advanced constitutive models.
- II. To develop and apply an energy-based optimization methodology ⁹ for determining optimal TMD parameters (mass ratio, stiffness, and damping) that maximizes ⁹ the performance of the TMD in seismic response reduction.
- III. To perform parametric studies for understanding the effect of:
 - Mass ratio on structural reduction
 - Placement of TMDs on different floor levels
 - Structural damping ratio and tuning frequency
- IV. To evaluate performance of the optimized 2-TMD configuration under seismic inputs, including:
 - Far-field broadband excitations (e.g., Taft 1952, El Centro 1940)
 - Near-fault pulse like motions (e.g., Kobe 1995)
- V. To investigate ⁶ the effectiveness of the MTMD system in terms of:
 - Peak roof displacement reduction
 - Inter-story drift mitigation
 - Base shear reduction
 - Energy dissipation efficiency

- VI. To formulate a framework that can be utilized for complex structures, which includes irregular buildings, and hybrid systems combining passive and active elements.

CHAPTER 2¹² LITERATURE REVIEW

2. This section provides a comprehensive overview of the existing literature on tuned mass dampers, tracing their theoretical development and practical applications in structural vibration control.

1) Gupta and Raheem (2024)

Gupta and Raheem evaluated the effectiveness of various TMD configurations on high-rise RC structure designed according to Indian Standard. The authors noted that seismic response reduction is an emergency field of interest. However, despite this advancement, a substantial gap remains in the literature concerning the seismic mitigating efficiency of various TMD topologies, specifically, floor-localized multiple tuned mass dampers versus spatially distributed MTMDs positioned vertically along the building height when applied directly to reinforced concrete (RC) frame structure.

The methodology involved designing high rise structures in ETABS and analyzing them for dynamic responses. The researchers obtained optimized parameters for the TMDs from previous studies and performed tuning based on the results obtained by modal analysis of base structure. A total of eight models were prepared, and the researchers conducted both harmonic and linear time-history analysis in horizontal directions. The earthquake records used for the analysis include the El Centro, North Ridge, and Loma-Prieta earthquakes. Performance was measured in terms of the achieved reductions in base shear forces, joint acceleration and relative structural displacements.

The results of the study provided clear evidence that multiple placements of TMDS perform better in seismic excitation than a single TMD unit. Notably, this investigation observed that the vibration-mitigating efficacy of the TMD system is highly sensitive to its vertical installation location along the structural height, with its ultimate performance being inextricably linked to both the specific floor assignment and the frequency content⁵

of the transient seismic excitation. By comparing the various configurations, the researchers concluded the MTMD systems have a promising role in energy dissipation of base excitation for RC frames. This research supports the move toward distributed dumping system to overcome the limitation of concentrated mass dampers in modern reinforced concrete design, where localized loads can be problematic.

2) Salcedo-Sanz et al. (2014)

Salcedo-Sanz et al. explored the mitigation of structural vibrations through the optimal calibration of Tuned Mass Dampers (TMDs) utilizing a novel co-evolutionary metaheuristic known as the Coral Reefs optimization approach enhanced with a substrate layer. The research was focused on the complex design and strategic placement of the TMDs in multistory building subjected to seismic excitations, as these structures frequently exhibit spatially distributed and closely spaced, natural frequencies that complicate traditional dynamic control.

The methodology suggests that for MDOF structures, conventional tuning theories like Den Hartog's are difficult to apply for multi-story structures due to the coupling dynamic interaction between the TMDs and multiple vibration modes of the primary structures. The CRO-SL algorithm was employed to search for the optimal mechanical properties and spatial placement of the dampers to maximize energy dissipation. The algorithm improves the vibration response by increasing the structure's damping and stiffness through forces generated by the damper's relative movement.

The findings of this study demonstrate that metaheuristic optimization is highly effective for complex structural system where modal coupling is present. By using the CRO-SL approach, the researchers were able to identify optimum TMD configuration that accounts for the unique model characteristics of multi-story buildings. The study concluded that for modern tall building, the design of the TMD is not obvious and requires these advanced

computational tools to ensure that the dampers are placed where they can most effectively counteract the multi model excitation triggered by earthquakes.

3) Kontoni and Farghaly (2023)

Kontoni and Farghaly investigated various methods to improve the earthquake resistance of tall RC and steel structures by utilizing the combination of shear walls, bracings and TMDs, while also considering Soil-Structure Interaction (SSI). The researchers aimed to evaluate how these various methods improve seismic resistance based on base shear forces, base moments, top-floor lateral ²displacements, relative to the fundamental period of the building.

The methodology compared stiffening methods with damping methods across different soil conditions. The investigation observed that incorporating SSI consistently elongates the fundamental period of RC structures relative to idealized fixed-base models, with RC structures exhibiting a significantly greater period elongation than in their steel counterparts. The researchers used numerical models to track the reduction in top flow displacement and the change in first mode period when TMDs were implemented at the top of the building.

The results of this research show that top-mounted TMD successfully increased the first more period time and reduced top displacements. Furthermore, the study also underscored that the steel frames being comparatively lighter and more flexible, inherently undergo amplified translational displacements. For RC high rise buildings, the researchers concluded that TMDs are a successful passive resistance method that can be effectively integrated into the design process to mitigate the adverse effect of seismic loads even when the flexibility of soil foundation is considered.

4) Jiang ¹⁹et al. (2024)

Jiang et al. investigated the seismic performance of a novel wall-integrated tuned mass damper applied to structures foundation on soft soil deposits, explicitly accounting for the dynamic effects of soil-structure interaction (SSI). The researchers noted that traditional TMD designs without considering SSI often suffer from a degree of mismatch, leading to limited response reduction or even dynamic amplification.

The methodology was centered on optimal calibration of wall-type Tuned Mass Damper parameters through the implementation of an advanced, multi-population Generic Algorithm. The researcher analyzed how soil flexibility alters the vibration and energy transmitted to the upper structure, finding that soft soil acts as an isolator, but also changes the frequency response of the building. The optimization process specifically targeted the dynamic response of the primary structure by minimizing objective functions such as the maximum roof displacement and the frequency response magnitude.

The results showed a significant reduction in structural response when SSI was considered during the optimization process. Reduction in both structural acceleration and displacement were found to be directly proportional to the peak seismic input, reaching maximum reduction of 13.45% for acceleration and 21.47% for displacement. Based on these empirical results, the researchers deduced that multi-population generic algorithms serve as a highly effective tool for configuring dampers specifically tailored for soft soil conditions, Where the damping ratio must be carefully tuned to account for the soil's isolating room while avoiding resonance mismatch.

5) Patsialis et al. (2021)

To efficiently optimize and evaluate the seismic performance of Tuned Mass Damper Inerters (TMDIs) in multi-story hysteretic buildings, Patsialis et al. systematically employed a nonlinear Reduce Order Model, evaluating its overall capacity to streamline the complex design and assessment process under transient ground motions.

The methodology compared the responses of structure with and without the TMDI using both linear and nonlinear ROMs, which were then validated against high-fidelity Finite Element Method models. The researchers found that while linear ROMs struggled to match FEM responses after the onset of hysteric behavior, the calibrated nonlinear ROMs provide an excellent match across the entire time-history. This allows for the efficient design of TMDIs that remain effective even when the RC structure undergoes significant nonlinear deformation.

The findings illustrated that the calibrated ROM can efficiently replace the original nonlinear FPM for the design as well as performance assessment of the TMDI. The study suggests advanced modeling techniques can be used to optimize MTMD system for RC frames that are expected to be nonlinear during strong earthquakes. This study confirms that the TMDI system provides a robust solution for controlling the seismic response of hysteretic multistory structures.

6) Kontoni and Farghaly (2023)

Kontoni and Farghaly examined the systemic control of structural vibrations utilizing tuned mass dampers, specifically extending their investigation to vertically and horizontally irregular buildings while explicitly accounting for the dynamic effects of soil structure interaction (SSI). This study specifically focuses on buildings with architecture irregularities, which often lead to complex torsional translation coupled response during an earthquake.

The methodology included a comprehensive study of TMD effectiveness for building 15 Stories under various ground motions. The researchers investigated the effect TMDs on different soil types to identify the most effective passive control configuration for irregular structures. The results suggest that TMDs are an effective passive resistance technique even when incorporated in highly irregular structures. It was shown that both soil

condition and structural reliability have important impacts on the response of the structure so that a user optimized damper is needed in these structures.

7) Shooshtari and Mortezaie

Shooshtari and Mortezaie made an analysis of ⁷ the effectiveness of linear **Multiple Tuned Mass Dampers (MTMDs)** for structures constructed of concrete where large hysteretic performance and degradation of stiffness could be observed under severe seismic events. Addressing the fundamental concern of whether MTMDs when tuned to a building's initial elastic frequency can maintain meaningful energy dissipation after structural period elongation, the metallurgy examined 10-story and 20-story reinforced concrete movement resisting frames. The structural simulations incorporate a Takeda hysteresis model to accurately capture the complex stiffness degradation and pinching effects characteristics of yielding RC components. Through inelastic time-history analysis under high intensity near field earthquakes, the researchers compared a conventional single large mass TMD against an MTMD system composed of five staggered-frequency units, utilizing total historical energy demands on the primary frame as the core performance index. The findings highlighted that while all TMD configurations suffer from off tuning as the host structure yields the distributed MTMD system is substantially more robust. By covering a broader frequency bandwidth, the MTMD configuration remains partially in resonance even as the building softens quantitatively reducing the total hysteretic energy demand on the RC frame by 22% compared to a merely 9% reduction achieved by the STMD. The authors concluded that MTMD efficiently provides a critical frequency buffer for yielding concrete structure, significantly increasing the global safety margin against collapse during extensive seismic excursions.

8) Sadek et al. (1997)

The study established by Sadek et al. introduced an effective criterion for selecting ¹⁶ the optimum tuning parameters of Tuned Mass Dampers (TMDs) subjected to seismic forces.

The nature of seismic excitation causes multi-mode response which is fundamentally different from harmonic response and in order to avoid this, the criteria for tuning , frequency and damping ratios are chosen in a way that it gives equal or ³ larger modal damping compared to the two complex modes of vibration.

Methodologically, ¹¹ the study computes dynamic response of various single degrees of freedom (SDOF) and multi degrees of freedom (MDOF) structures equipped with TMDs, under multiple historical earthquake records. To provide a practical tool for design engineers and circumvent the need for complex, site-specific numerical optimization. Sadek et al. utilized curve fitting to derive simple, closed-form equations for estimating optimum parameters. The authors also explored the mega-substructure configuration, demonstrating that utilizing upper building segments as vibration absorbers can effectively manage dynamic demands. The findings confirmed that balancing the damping in first two modes significantly attenuates both displacement and acceleration responses, reducing structural demands by up to 50% and establishing a highly reliable baseline for modern TMD design in high-rise buildings.

9) Salvi and Rizzi (2015)

Noting the effectiveness of passive TMDs under unpredictable, broadband ground motions remains a debated topic, Salvi and Rizzi investigated the optimum tuning of these devices for framed structures subjected to a seismic excitation. The methodology features a closed-loop procedure with MATLAB, coupling a time domain integration solver with a Minimax optimization algorithm. To achieve the optimum anti-seismic performance, the researchers set their objective function ³⁶ to minimize the Root Mean Square (RMS) displacement ³³ of the top floor. Testing on benchmark single degree of freedom (SDOF) and multiple degrees of freedom (MDOF) shear-type structure under the 1940 Imperial Valley earthquake and other recent strong motion records demonstrated that optimum tuning of a given seismic input is theoretically possible, yielding responses reduction between 20% to 50%. A key discovery was that for seismic inputs, the optimal frequency

ratio was larger and the TMD damping ratio was smaller than those prescribed by classical harmonic tuning. The observation that even with distinct parameters of optimization it provides a similar reduction as by classical methods.

10) Fahim Sadek, Bijan Mohraz, Andrew W. Taylor, and Riley M. Chung

Authors addressed a significant gap in the application of classical vibration control theories to seismic engineering. Traditional tuning methods, particularly Den Hartog's formulas, were originally designed for machines or structures experiencing steady-state harmonic vibrations. In contrast, seismic events involve transient, random, and broadband energy, which requires a different tuning philosophy. The primary aim of this research was to establish a method for estimating optimal Tuned Mass Damper (TMD) parameters that achieve equal and maximized modal damping in the first two complex modes of a structure-TMD system. This strategy ensures efficient energy dissipation in the modes that most significantly contribute to the seismic response.

The researchers employed a rigorous numerical optimization procedure, treating the tuning frequency ratio and damping ratio of the TMD as free variables for a given mass ratio. By solving the characteristic equations of a two-degree-of-freedom (2-DOF) system, which represents the first mode of a building and the TMD, the authors identified parameter sets that yield equal modal damping ratios in both emerging complex modes. This "equal damping" criterion is crucial as it prevents one mode from being underdamped, which could permit significant oscillations at that frequency. Through extensive curve-fitting of numerical results, Sadek et al. proposed simplified design formulas. For an undamped primary structure, the optimal tuning ratio and damping were provided. For structures with inherent damping, they presented an adjusted formula.

The effectiveness of these formulas was confirmed through time-history analyses of single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) structures subjected to various earthquake records, including El Centro and Northridge. The findings demonstrated that TMDs tuned with these seismic-specific formulas consistently reduced peak displacements and accelerations more effectively than Den Hartog's tuning. Additionally, the study investigated the "mega-substructure" configuration, where architectural components of a tall building function as mass absorbers. This innovation allows for vibration control without the economic and spatial challenges of adding large dedicated weights, significantly enhancing the practical utility of TMD technology in high-rise construction.

11) Yoyong Arfiadi and Muhammad N.S. Hadi

expanded the field of structural control by exploring the simultaneous optimization of passive and active systems for three-dimensional buildings. Their research acknowledged that while passive TMDs are highly reliable, active control systems, which utilize external power to apply forces, can theoretically achieve superior performance. Utilizing Hamilton's principle, they derived the complete equations of motion for complex 3D structures, incorporating translational and torsional coupling. The primary challenge of the research was to determine the optimal placement and characteristics of the dampers alongside the optimal gain for the active controllers.

The methodology employed a Genetic Algorithm (GA) as the optimization tool, capable of navigating large, non-convex search spaces without the need for gradient information. The optimization process considered three distinct performance norms: minimizing total output energy, minimizing peak frequency response, and minimizing peak time response. By treating the damper's mass, stiffness, damping, and active control gains as chromosomes in GA, the researchers identified configurations that minimized structural drift under various objective functions.

A key insight from this study was the comparison of trade-offs between passive and active control systems. The authors found that while active systems could achieve reductions of 20-30% in peak responses, passive TMDs optimized via GA proved remarkably effective, offering the distinct advantage of "inherent safety," as they remain operational even if power is lost during an earthquake. Their numerical simulations for a 3D building frame demonstrated that the GA could identify unique and non-intuitive damper placements that specifically targeted torsional modes. This research emphasized the need for careful management of the center of rigidity and center of mass in 3D buildings through strategic control device placement to prevent localized damage at the building's periphery.

12) ¹⁶ Mahendra P. Singh, Sarbjeet Singh, and Luis M. Moreschi

focused on optimizing TMD systems for "torsional buildings," which are characterized by misalignment ⁶ between the center of mass and center of stiffness. Such buildings pose significant control challenges, as seismic forces induce rotational motions that amplify displacements at the edges. The researchers proposed a configuration of four TMDs, arranged in two orthogonal pairs, providing the necessary degrees of freedom to control both translational and rotational vibrations.

The methodology adopted a stochastic approach, representing the bi-directional seismic input through a power spectral density function. The optimization process involved 14 design parameters, including mass, stiffness, damping, and planar coordinates for each of the four dampers. Given the complexity of this search space, the researchers employed a GA to minimize several performance functions, such as maximum story drift and base shear. Unlike previous studies that positioned TMDs at the center of mass, Singh et al. discovered that optimal placement is often eccentric. By locating dampers closer to flexible edges, the system can effectively "re-balance" the building's dynamic eccentricity.

Their findings confirmed that GA-optimized TMDs significantly outperformed those designed using traditional tuning rules, which often falter in asymmetric structures. Specifically, the optimized four-TMD system reduced peak localized drift by up to 40% more than a single centered TMD of equivalent total mass. This research validated the application of evolutionary algorithms in addressing complex, multi-parameter structural control problems and provided a clear strategy for safeguarding asymmetric buildings prone to torsional failure.

13) ¹⁸ Jerod G. Johnson, Lawrence D. Reaveley, and Chris P. Pantelides

They introduced ¹⁸ the Rooftop Tuned Mass Damper Frame (RTMDF), an innovative structural solution for retrofitting existing buildings. The RTMDF concept involves constructing a stand-alone steel or concrete frame atop a building, serving as a large mass damper. This approach is particularly beneficial for buildings where adding substantial internal mass is physically impractical or architecturally unappealing. The research aimed to develop a design methodology leveraging standard engineering tools such as site-specific response spectra and pushover analysis.

The methodology involved modeling the building and the rooftop frame as a coupled system. The researchers utilized non-linear static (pushover) analysis to ascertain ² the yield point and post-yield stiffness of the building. ¹⁷ They then adjusted the stiffness and mass of the RTMDF to shift the building's fundamental period away from the peak energy region of the design earthquake. A significant finding was that the RTMDF could be tuned to achieve substantial damping even with relatively low mass ratios, provided the frame's period was accurately matched to the modified period of the building.

The study concluded that RTMDF represents a highly cost-effective retrofit strategy. As the "damper" is a structural frame, it can serve dual purposes, such as functioning as a mechanical penthouse or architectural feature.

Experimental tests on a scaled model confirmed that the RTMDF could reduce roof displacements by over 30%, while significantly decreasing the ductility demand on the building's primary columns. This research offered a practical, large-scale implementation of TMD theory that addresses real-world construction and economic challenges.

14) **Julio C. Miranda**

Miranda's 2005 paper specialized in ⁴³ an energy-based approach for the optimal design of TMDs. He argued that for seismic protection, the objective should not just be to reduce peak displacement, but to maximize the energy dissipated by the control device relative to ⁴⁵ the total energy input by the earthquake. He developed a 2DOF mechanical model representing the building's first mode and the TMD, formulating the problem in terms of energy balance equations.

The methodology utilized an iterative numerical procedure to find the damping and stiffness values that maximize the "damping ratio enhancement". By analyzing the energy flow, Miranda discovered that there is a specific "optimal damping" value beyond which the TMD becomes too rigid and begins to act as a part of the primary structure rather than an absorber. His results showed that the energy-based optimal parameters led to a more rapid decay of structural oscillations after the initial shock.

A significant contribution of this work was the comparison between the energy-based results and traditional stochastic results. Miranda found that while the mathematical derivations were different, the final design parameters were very similar, validating the energy-based approach as a simpler and more intuitive tool for structural designers. He concluded that maximizing modal damping is the most reliable proxy for structural safety in seismic zones, as it directly mitigates the risk of cumulative fatigue and structural degradation.

15) ³¹ **Min-Ho Chey, J. Geoffrey Chase, and John B. Mander**

Chey ⁴⁷ et al. investigated the "robustness" of semi-active tuned mass dampers versus passive systems. Passive TMDs are highly sensitive to "detuning"—

if the building's stiffness changes (due to earthquake damage) or was modeled incorrectly, the passive TMD loses its effectiveness . The researchers evaluated an SATMD that uses a variable-orifice damper to change its properties in real-time based on structural feedback .

The methodology involved time-history analyses of several buildings subjected to a suite of 20 ground motions, representing 84th percentile seismic demands . They used mass ratios as high as 8% to test the upper limits of control performance . The findings were definitive: the SATMD provided much more consistent performance across different earthquakes and was far less sensitive to modeling errors . While the passive TMD performed well when perfectly tuned, its effectiveness dropped by nearly 50% when the building's frequency shifted by just 10% .

However, the authors noted an interesting trade-off: passive TMDs sometimes produced better acceleration responses in the top floors because they provide a smoother damping force than the "switching" forces of semi-active systems . Despite this, the study recommended SATMDs for critical infrastructure where structural survival is the priority, as they ensure that the damping ratio remains high regardless of the building's degraded state during an event .

16) ⁵ **Maurizio De Angelis, Salvatore Perno, and Anna Reggio**

This study pioneered **the** concept of "large mass ratio" TMDs . While traditional TMDs typically use a mass ratio of 1% to 2%, De Angelis et al. proposed using ratios of 10% or even higher . They suggested that instead of adding new mass, engineers should repurpose existing heavy components—such as large mechanical equipment, water tanks, or helipads—and mount them on flexible, damped bearings to act as the absorber .

The analytical methodology investigated ²³ **the dynamic response of structures** equipped **with** these massive absorbers . The researchers found that ²³ **as the mass ratio increases, the "effective bandwidth" of the TMD widens** significantly . This means that the damper becomes effective across a broader range of frequencies, making it naturally immune to the detuning effects that plague smaller TMDs . In seismic events where the building's frequency

drops due to nonlinear yielding, the LMR-TMD remains "in tune" because of its wide operational range .

Numerical simulations of an MDOF structure confirmed that LMR-TMDs could reduce the variance of structural response by up to 70%, far exceeding the 20-30% reduction typical of standard TMDs . The study concluded that repurposing existing architectural masses is a "virtuous" engineering practice that enhances seismic resilience without the material cost and structural load penalty of adding dedicated ballast .

17) Miranda

Miranda proposed a tuning methodology that identifies a "point of multiplicity" for complex eigenvalues and eigenvectors in mechanical systems. This research establishes damping and tuning parameters that remain unaffected by specific seismic excitations. The methodology shows that achieving high damping can occur by equalizing modal damping ratios for systems with damping coefficients below the multiplicity condition, providing a robust strategy for mitigating seismic responses across various building technologies.

18) Moutinho

Moutinho examined "non-traditional" ⁶ large mass ratio Tuned Mass Dampers (TMDs) as a more effective solution for earthquake engineering, even though small TMDs often address wind vibrations. The proposed method establishes a direct relationship between the ³ mass ratio and the damping ratios of the structure's first two vibration modes. By equalizing these ³ modal damping ratios, ³ the system enhances its robustness against uncertainties and facilitates the application of simplified analysis methods such as response spectrum.

19) Rakićević et al.

This study integrated shaking table testing and analytical modeling to assess the effectiveness of TMDs. The researchers noted that while a single TMD at the roof level is a common choice, employing multiple TMDs significantly enhances the reduction of structural responses. Their analysis indicates that the effectiveness of the damping system heavily relies on the frequency content of earthquake excitations, reinforcing the superiority of optimally tuned mechanical properties over standard non-optimized configurations.

20) Salvi and Rizzi

Salvi and Rizzi addressed the ongoing discussion regarding TMD effectiveness in seismic contexts, highlighting that traditional tuning often relies on ideal loadings, such as white noise. They employed numerical minimax optimization algorithms to assess TMD parameters for damped primary structures. Their findings emphasize that seismic assessment remains an open area of research, with contemporary methods increasingly incorporating actual earthquake records into the tuning process to address the limitations of classical theories.

21) Xiang and Nishitani

Xiang and Nishitani recognized that standard TMDs primarily perform well for wind or post-earthquake decay. They focused on "non-traditional" TMDs designed for response control during significant seismic events. Specifically applied to base-isolated and high-rise structures, the Non-Traditional TMD (NTTMD) aims to provide continuous control during intense phases of ground motion, expanding beyond the traditional functions of TMDs in civil engineering.

22) Kamgar et al.

Kamgar et al. introduced an optimization approach centered on the "critical earthquake," representing the most intense excitation a structure may encounter throughout its lifespan. By utilizing advanced algorithms, such as

the Grey Wolf Optimizer and Enhanced Colliding Bodies Optimization, they optimized TMD parameters to minimize maximum roof displacement. The results demonstrated that these bio-inspired and physics-based methods yield more economical and efficient designs compared to classical approaches like Den Hartog or Warburton.

23) Elias et al.

This research investigated ⁵ Distributed Tuned Mass Dampers (d-MTMDs) for multi-mode control. Elias et al. discovered that optimally designed Multiple Tuned Mass Dampers (MTMDs) outperform a single TMD with an equivalent total mass. Key findings indicate that increasing the mass ratio requires higher damping, while increasing the number of TMDs broadens the frequency bandwidth, effectively mitigating accelerations even at lower floor levels when distributed according to mode shapes.

24) Salehiziarani and Karami Mohammadi

In their study, the authors aimed to determine the optimal mass and damping ratios for systems subjected to the El Centro 1940 earthquake. They found that large masses could significantly decrease peak responses, even if not perfectly tuned to the dominant frequency. The authors also proposed establishing a semi-active mechanism that allows for real-time adjustments in damping, which can reduce displacement across a wider range of input frequencies compared to fixed passive TMDs.

25) Domizio et al.

Domizio et al. explored TMD performance in nonlinear structures characterized by stiffness degradation. Through Particle Swarm Optimization, they determined that a configuration featuring two TMDs in series, tuned to 50% of the fundamental frequency, is most effective when ductility demand exceeds 5. For medium-period structures, a 25% mass ratio

successfully achieved a 26% reduction in median ductility demand under far-field records.

26) Araz and Kahya

This study employed the Simulated Annealing algorithm to design series TMDs. To avoid excessive floor heights in practical applications, the number of dampers in a series was restricted to two. Araz and Kahya observed that as the mass ratio increases, the optimum frequency of the second TMD unit rises while that of the first unit decreases, and the optimum damping ratio of the second unit consistently exceeds that of a traditional single TMD.

27) Rahmani and Konke

Rahmani and Konke identified the need to protect tall buildings against natural hazards and showed that while new code practices use inelasticity to decrease seismic forces, they often cause serviceability problems. They concentrated on installing Distributed Multiple Tuned Mass Dampers (d-MTMDs). They compared these with Single Tuned Mass Dampers, which often control only one vibration mode because their effectiveness depends on location and tuning to the fundamental frequency. Their findings indicate that tall buildings, while enough stiff for wind forces, do not have sufficient lateral stiffness to resist significant earthquake motion, hence a distributed system was proposed that provides an affordable and feasible way to retrofit a building to enhance its service life.

28) Rahimi et al.

In a state-of-the-art review, Rahimi et al. collected findings from a range of papers including Elias and Matsagar. They concluded that placement is crucial in a Single Tuned Mass Damper, and the optimal position is on a level with the maximum modal displacement and tuned to the correct frequency.

The trend is that ¹increasing the mass ratio of the STMD continually improves structural responses such as floor acceleration, ¹⁵inter-story drift, and base shear. They also noted a consistent trend across the literature indicating that ¹increasing the mass ratio of the STMD enhances performance metrics such as floor acceleration and base shear. Additionally, they examined ⁴⁰the double criteria that forms the equivalent linearization method proposed by Anh and Nguyen to determine optimal tuning ratio. Which simplifies the design of TMDs by substituting complex damped system with simpler undamped system .

29) Sano et al.

Sano et al. Proposed a new "friction fail-safe mechanism" that could be installed in high-rise buildings. A risk associated with TMD is that if the displacement of a TMD reaches its design limits during extreme seismic loading, it may result in severe collisions with the building frame and cause catastrophic failure. This fail-safe mechanism permits sliding of the TMD base when the force reaches a threshold. As the base slides, friction force between the building and the TMD is limited, and mechanical energy from the system is dissipated as friction heat; this supplemental damping effect protects mounting hardware from failing during excessive movement .

30) ¹⁹Pandit et al.

Pandit ¹³et al. Investigated the effectiveness of a hybrid TMD + TLD system that was applied to an MDOF structure. The system consists of an optimal Single Tuned Mass Damper ³mounted on the top floor and an optimal Tuned Liquid Damper ²⁰mounted on the fourth floor of a five-story building model. They found the system to be most effective when the TMD is tuned to the fundamental frequency of the building and the TLD is tuned to the second mode. The hybrid system effectively suppresses motion over a broad frequency range with relatively little mass added to the structure. This strategy successfully mitigates vibration across a broader frequency range

when compared to a single device, enhancing the seismic resilience even with low mass ratio.

31) Kontoni and Farghaly

Kontoni and Farghaly investigated the seismic control of non-regular steel tall buildings with Soil-Structure Interaction (SSI). The response was optimized with various objective functions and the best proved to be the norm of the roof displacement transfer function as opposed to an algorithmic optimization which performed better in near-fault and far-fault earthquakes . They also addressed the issue of seismic pounding between two tall buildings and observed that proper TMD placement can significantly alleviate building damage and reduce risk in dense population.

32) Abrass and Lavan

Abrass and Lavan introduced a tuned inertial mass electromagnetic transducer system which functions as a damp outrigger for high-rise buildings. The device works as an electromagnetic motor driven damper that uses linear motors to transfer vibration kinetic energy into electrical energy . The optimization framework utilized was a frequency domain approach, based on the Lyapunov equation; this was compared to traditional algorithmic techniques and found to effectively determine optimal number and placement of devices . It also serves to obtain 'green energy' from wind excitation during periods when seismic input is minimal .

33) Pappas

The work described in Pappas study examines the effectiveness of a TMD on buildings with varying natural periods through a comprehensive study in ETABS software. Resonance is found to be the primary cause for increased deformation. It was concluded that the TMD provides consistent, steady reduction in displacement regardless of seismic input . Pappas determined

that for an engineer it is imperative to use correct understanding of the behavior based on natural periods and mass ratios during initial design .

34) Kaveh et al.

Kaveh et al. argued that structures must be controlled using MDOF models as opposed to SDOF models to ensure robust designs. The used metaheuristic algorithms (Particle Swarm Optimization and Chaotic Optimization) to identify and achieve minimal roof displacement along with optimization of non-standard design criteria such as CO₂ emissions produced during the fabrication of control devices .

35) Anh and Nguyen

Anh and Nguyen introduced the traditional formulation to the problem of designing an optimal tuning ratio for TMDs in a damped linear structure. They proposed a closed-form expression for optimal tuning ratio, analytical solutions, based on equivalent linearization, were developed for base and direct force excitation, the formulation serves as a the bedrock for subsequent numerical simulations .

36) Elias and Matsagar

Elias and Matsagar's study on the high-rise buildings shows the effectiveness of distribution on an MDOF system, when it comes to effective implementation of multiple TMDs the solution is not simply an increase in mass, but an alignment of the TMD with modal responses that is even when maintaining an constant mass ratio and distributing the mass ratio into several small units when placed at optimum location yields a more stable reduction in response across different earthquake records and concluded that the best solution for a given total mass ratio was achieved through multiple distributed TMDs rather than a single large one .

CHAPTER 3: OVERVIEW OF SOFTWARE

3.1. Structural Modelling via OPENSEES:

To achieve our objectives, the structure is modelled in ¹² OPENSEes (Open System for Earthquake Engineering Simulation) in the python programming language. The reason is that the OPENSEes has fast processing, open-source nature of the software and the accuracy with which it calculates the results. However, accurately modeling ² reinforced concrete (RC) frames subjected to severe seismic loads is highly challenging due to simultaneous occurring multiple complex failure modes, including concrete cracking, core crushing, structural bond-slip failure, and pinched hysteretic responses. To rigorously capture these physical realities and their combined influence on global strength and stiffness degradation, the following modelling techniques are executed within the OPENSEes framework:

- **Elemental Formulation:** The RC frame members (columns and beams) are modeled utilizing the nonlinear force-based fiber beam-column elements, which allow plasticity to distribute along the length of the members to replicate actual yielding behaviors.
- **Material Models:** The uniaxial constitutive model *Concrete02* is used to capture the non-linear compressive and tensile behavior of unconfined cover and confined core concrete. The *Steel02* material is employed to simulate the yielding, isotropic strain-hardening, and cyclic degradation of the longitudinal reinforcing steel.
- **Hysteretic and Pinching Behavior:** Under severe cyclic excursions, RC joints experience severe stiffness degradation. To consider this effect, the *Pinching4* uniaxial material is adopted. This model accurately captures unloading stiffness degradation, reloading stiffness degradation, and cyclic strength degradation.
- **Shear behavior:** To replicate the complex axial-flexural-shear interaction and cyclic shear failure of non-ductile columns, the shear force-deformation behavior

is modeled using the *ModIMPinching* (Modified Ibarra-Medina-Krawinkler) material model.

3.2. Fundamental Steps for Modeling a Structure in OPENSEesPy

The basic steps for setting up and executing the simulation of the RC frame were done in the OPENSEes framework. Following are the steps for establishing the computational model systematically executed as follows:

- **Model Initialization:** Defining the number of dimensions (ndm) and the number of degrees of freedom per node (ndf) in the very beginning of our program.
- **Node Definition:** Next we define all the nodes of our structure. Node definition includes giving a proper address to each of them through the use global coordinate system.
- **Element definition:** We define the elements used to create the beam, columns or slab in the structure. There are several options available in the Basic Builder package, but we have used the nonlinear force-based beam column as our element. These elements incorporate distributed fiber sections to accurately capture inelastic yielding and post yielding behavior of the reinforced concrete members during dynamic excitation.
- **Material Definition:** Here, in our structure we have not specifically defined the material but rather club the characteristics of the material such as area of cross section (A), modulus of elasticity of the material E and the moment of inertia of the member (I) in the element itself by using specific constitutive material models (Concrete02, Steel02, etc.)
- **Boundary Conditions:** The boundary conditions of the building are defined. For the multistory frame. The global nodes at the bottom of the structure are completely restrained against both translation and rotation, simulating a perfectly fixed support condition at the foundation level.

- An all-important step follows called matrix transformation, where we have different ways to convert all the local coordinates into global coordinates.
- We therefore apply all the loads using time series and patterns as well as nodal mass on the structure.
- Recorders are used to store the output of our program where a separate file is created at the specific location containing the specified parameters such as reaction, displacement or drift at different time step of applying the load.
- The core of the program includes definition of analysis object. It has several key components like constraints, numberer system, algorithm, etc. which needs to be specified carefully depending upon our structure.
- In the end, we run our analysis in 'n' number of steps depending upon the load increment.

After modeling the structure within the OPENSEes environment, a static gravity analysis must be performed to establish the initial stress state and structural equilibrium before any dynamic lateral loading is applied. Gravity loads are applied incrementally (e.g., Utilizing a load factor increment of 0.1 units per step). The exact increment value depends heavily on the required convergence tolerance; increasing the number of analysis steps or decreasing the load increment per step drastically enhances numerical stability, through it concurrently increases the overall computational processing time.

3.3. Modeling the 2-TMD System

Instead of using external software for the dampers, the 2-TMD units are integrated directly into the building's structural matrix using OPENSEes build-in link elements. The secondary masses representing the TMDs are attached to the roof nodes using Zerolength elements. Within these zero-length elements, appropriate uniaxial elastic materials are assigned to act as the TMD's tuned stiffness (springs), and uniaxial viscous materials are assigned to act as the TMD's damping (dashpot). This capability enables OPENSEes to

natively model the coupled dynamic response between the primary structural system and the mass dampers under the seismic excitation.

3.4. Modular Computational Script Architecture

To reduce the complexity of our script and make it easy to maintain, all codes were separated into modular supporting files for different structural model parameters.

This supporting file includes.

- **Dimensional Units Script:** A file containing the derived dimensional variables to ensure strict unit consistency (e.g., force, mass, length, time) throughout the analysis.
- **Gravity Analysis Script:** A file defining the analysis objects, integrators and algorithms required to incrementally apply the static gravity loads prior to dynamic analysis.
- **Modal Analysis Script:** A file containing the modal analysis (eigenvalue analysis) module to extract ¹²the structure's natural vibration frequencies and fundamental mode shapes, this provides the precise target frequencies required for tuning the TMD.
- **Dynamic Excitation Script:** A file containing the code to assign mass and stiffness proportional Rayleigh damping to the structure, as well as commands to apply the unidirectional or bidirectional seismic ground excitation to the base nodes.
- **Data Processing Script:** A data processing script utilized to convert and format the raw earthquake time- history data, obtained from IIT Delhi earthquake database into a suitable digital format that the OPENSEESPy solver can directly read and process.

CHAPTER 4: Mathematical Formulation and Structural Modeling

4. Introduction

Following the software overview detailed in chapter 3, this chapter establishes the rigorous mathematical framework and structural modelling techniques programmed into the computational platform. To evaluate the vibration-mitigating capabilities of the 2-TMD (dual Tuned Mass Damper) system, it is essential to define the equations that govern the motion for the primary structure having multi-degree-of-freedom (MDOF). Furthermore, establishing the state-space representations is crucial for facilitating the specific energy-based optimization routines utilized to perfectly tune the dampers against seismic excitations.

4.1. Problem Statement and Structural Description

A six-story, three-bay ³⁴reinforced concrete (RC) building is considered for this study to evaluate ²⁷the proposed structural control methodology. To mitigate vibration induced by seismic load, a 2-TMD system is analytically installed at the top story of the primary structure. Recent studies demonstrate that dividing a singular mass into a 2-TMD configuration increases the system's robustness against frequency mistuning and enhances its ability to control higher order modes during broadband excitations.

For computational efficiency with OPENSEes, the front interior frame is extracted and idealized as a two-dimensional portal frame. The primary properties of the structured member are defined as follows.

- **Grade of concrete:** M30.
- **Dimensions of ²⁷beams:** 300 mm width x 400 mm depth.
- **Dimensions of columns:** 400 mm x 400 mm.
- **Height of column:** 3m (per story)
- **Length of beam:** 5m (per bay)

- Zone V

Table 1: Material properties of structure model

Material / Component	OPENSEESPy Model	Parameter	Value
Concrete (Core & Cover)	Concrete02	Compressive Strength (f_c)	30 MPa
		Strain at Peak Strength (ϵ_c)	0.002
		Crushing Strength (f_{cu})	6 MPa
		Crushing Strain (ϵ_{cu})	0.006
		Nominal Clear Cover	40 mm
Steel Reinforcement	Steel02	Yield Strength (f_u)	415 MPa
		Elastic Modulus (E_s)	200 GPa
		Strain-Hardening Ratio (η)	1.0%
Column Elements	NonlinearBeamColumn	Cross-Section (Width $\times$ Depth)	400 $\times$ 400 mm
Beam Elements	NonlinearBeamColumn	Cross-Section (Width $\times$ Depth)	300 $\times$ 400 mm

Before conducting dynamic simulation, a static gravity analysis is performed. At the final step, the total effective seismic weight of the multi-story building is determined to be 1060 kN. We assume the total mass ratio (μ_{total}) for the control system is 5%. So the required total weight for the damper system is 53 kN, that is divided into equal parts between the two TMD units at the roof level, each weighing 26.5 kN.

Elevation View: 6-Story RC Moment Resisting Frame

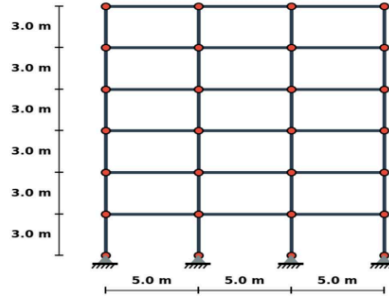


Figure 1: Elevation of structural model

4.2. Mathematical Formulation of the MDOF System

The dynamics of a MDOF structure can be characterized at a specific moment in time, denoted as (t) , where the total external forces acting on the structure are counterbalanced by the interplay of the structure's mass, damping, and stiffness forces. When an earthquake-induced dynamic load is applied to the structure, the governing equation of motion can be expressed as follows:

$$[M_m] \{\ddot{u}(t)\} + [C_m] \{\dot{u}(t)\} + [K_m] \{u(t)\} = - [M_m] \{b\} \ddot{u}_g(t)$$

Where:

- $[M_m]$, $[C_m]$, and $[K_m]$ represent the mass, damping, and stiffness matrices of the primary system, respectively
- $\{\ddot{u}(t)\}$, $\{\dot{u}(t)\}$, and $\{u(t)\}$ denote the relative acceleration, velocity, and displacement vectors.

- $\{b\}$ is an influence vector that couples the ground motion to the structural degree

The form of these equations can be simplified to the first order ordinary differential equations representing a state-space system:

$$\{\dot{x}\} = [P] \{x\} + [Q] \ddot{u}_g(t)$$

Where $\{x\}$ is the state vector, $[P]$ is a state matrix, and $[Q]$ is the input matrix. This formulation allows computational software to efficiently minimize the primary structure's displacements.

4.3. Integration of the 2-TMD system

When a passive mass damper network is attached to the primary frame, it introduces additional degrees of freedom (DOFs) to the overall system. Based on our established research parameters, a 5% mass ratio is distributed across a 2-TMD configuration.

In modelling these dual dampers, literature identifies two highly effective arrangements: the parallel (2P) configuration, wherein two discrete auxiliary masses are independently connected in the primary structure and the series (2S) configuration where the two masses are connected in series to the main structure. Regardless of the chosen architecture topology, the response and vibration-mitigating capacity of the i^{th} component of the TMD system are fundamentally governed by three critical design parameters i.e. the individual mass ratio (μ_i), the frequency tuning ratio (α_i), and the mechanical damping ratio (ζ_i). These are defined as the following:

$$\mu_i = \frac{m_i}{m_s}, \quad \alpha_i = \frac{w_i}{w_s}, \quad \zeta_i = \frac{c_i}{m_i w_i}$$

Where c_i , m_i , and k_i are the damping, mass and stiffness of the i -th TMD, and m_s and w_s are the mass and fundamental frequency of the main structure. By utilizing Zerolength

link elements to superimpose the 2-TMD properties natively within OPENSEES, the structural matrices are automatically expanded to account for auxiliary devices.

4.4. Energy-Based Optimization of 2-TMD Parameters

Because classical tuning theories were primarily derived from undamped structures under a steady-state harmonic loads, they are generally sub-optimal for chaotic seismic excitations. Therefore, this research utilizes an energy-based optimization approach.

Achieving optimal TMD performance characterized by maximizing the power flow from the primary structure to the damper is fundamentally equal to minimizing the mean-square velocity response of the primary structure. Within this energy base optimization framework, the difference between the input excitation power guaranteed by the external ground motion (A) and kinetic powers successfully transferred to the secondary mass (B) is formally defined as the Residual energy (E_m) of the two-mass system.

$$E_m = \{A-B\}$$

By establishing algorithms to set this Residual Energy (E_m) close to zero , an iterative search can be conducted to find the optimum TMD mass, stiffness, and damping parameters that yield the highest kinetic energy dissipation during earthquake. Within this energy balance framework, the transfer of a dynamic power into the secondary mass reaches its maximum limit only when the relative displacement of the damper lags the primary structure's motion by a precise 90-degree phase angle.

4.5. Applied Loading Protocols and Critical Earthquake

To fully vet the structural control capabilities, robustness, and energy dissipation efficiency of the 2-TMD network, the computational models are subjected to transient seismic ground motions. Because structural responses are highly dependent on the spectral characteristics of seismic inputs, the paradigm of the critical earthquake is implemented.

The critical earthquake for any given structure can be simply defined as the earthquake which causes the largest response demand from the structure. A TMD will be optimized when it can safeguard the structure under peak roof response caused by a critical excitation, as well gives satisfactory results under various historic records.

4.6. Analytical Procedure and Assessment Framework

This analytical procedure is executed natively within OPENSEes:

- i. **Gravity Analysis:** The gravity loads are added incrementally to provide the initial axial forces and static equilibrium state before adding dynamic loads, which results in the correct effective seismic weight for tuning the 6% mass ratio of the 2-TMD system.
- ii. **Modal (Eigenvalue) Analysis:** Solves the eigenvalue problem to extract the building's natural time-period (T_n), natural circular frequencies (ω_n), and mode shapes (ϕ_n), which are crucial for defining the exact target tuning frequencies for the 2-TMD system.
- iii. **Nonlinear static (Pushover) Analysis:** A nonlinear static analysis is executed by applying an incremental lateral load pattern to derive the structure base shear versus root displacement capacity curve. By tracking the sequence of the component yielding and plastic hinge formation, this analysis systematically classified the global structural response into distinct limit states, namely Operational(SLO), Damage control (SLD), Life safety (SLV) and Collapse prevention (SLC).
- iv. **Non-Linear Time History Analysis (NLTHA):** Base nodes of the computational model are subjected to the empirical ground acceleration records of the chosen seismic events using Newmark's step-by-step method of integration. The transient dynamic evaluation computes the exact time-varying reduction in peak roof displacement, inter-story deformation demands, and total base shear afforded by the supplemental multiple tuned mass dampers system. To comprehensively

quantify the control effectiveness, the evaluations monitor both ⁶the peak maximum and the Root Mean Square (RMS) magnitude of the absolute kinematic responses specifically ²displacements, velocities, and accelerations of the roof.

- v. **Energy Response Assessment:** To validate the energy-based optimization of the 2-TMDs, an energy balance equation is computed throughout the time history. The software tracks the temporal evolution of the relative seismic energy input, as well as the structure's kinetic and elastic potential energies. Most importantly, it calculates the exact quantity of energy attenuated by the primary structure's inherent damping mechanisms, as opposed to the supplemental hysteretic energy successfully dissipated by the viscous dashpot of the TMD system.
- vi. **Sensitivity Analysis:** Because traditional TMDs are highly sensitive to frequency detuning caused by structural yielding, the optimized TMD parameters (stiffness and damping) are deliberately subjected to parameter uncertainties. The models are re-analyzed to confirm that the large-mass 2-TMD configuration remains robust and sustains high levels of response reduction even when off-tuned.

4.7. Applied Loading Protocols

To evaluate the robustness of this energy-based 2-TMD configuration, the software model is subjected to Non-Linear Time History Analysis (NLTHA) using the suit of 8 historical records established into our methodology:

Earthquake Record	Event Date	Recording Station	Component	PGA (g)
Ardal	06-04-1977	Naghan 1	Long	0.89
⁶ Denizli	19-08-1976	Denizli-Bayindirlik ve Iskan Mudurlugu	NS	0.338
Imperial Valley	18-05-1940	El Centro	0	0.596

Kobe	17-01-1995	JMA	NS	0.818
Off coast of Levkas	24-08-1988	Lefkada Hospital	TRAN	0.236
Provadja	10-11-1983	Provadja-Clock Tower	TRAN	0.254
Kern Country, CA	21-07-1952	Taft Lincoln School Tunnel	TAF 111	0.176
Uttarkashi	19-10-1991	Uttarkashi	N15W	0.237

CHAPTER 5 : RESULTS AND DISCUSSION

5. Structure analysis

5.1. Gravity Analysis:

Before conducting the nonlinear dynamic time-history evaluations, a rigorous gravity analysis was done to determine the initial stress-state of the structure and to ensure strict equilibrium within the OPENSEESPy domain. The residential distributed load of 1200 kg/m translated to lump mass allocation of 3000 kg at the exterior nodes and 6000 kg at the interior nodes of each respective floor level.

The numerical implicit algorithm converged properly, thereby indicating a state of perfect static equilibrium. The vertical deflection of the frame for the prescribed service load conditions was negligible (about 0.8456 mm), indicating that the column elements are axially stiff and confirm that the fixed base support condition were incorporated correctly into the numerical solution.

5.2. Pushover Capacity Analysis

To assess the nonlinear yielding progression and the ultimate lateral capacity of the multi-story reinforced concrete (RC) frame, a nonlinear static use of analysis is performed. The developed capacity curve that plots the overall base shear against the overall base shear against the overall roof displacement shows how the progressive damage of the frame occurred according to the established performance limit states. Additionally, the summary of the pushover capacity reveals a peak based shear capacity of 3918.12 kN at a roof displacement of 896.02 mm. The coordinate of the maximum displacement signifies the collapse prevention limit (SLC) of the bare frame, indicating the critical threshold at which the cumulative formation of the plastic hinges results in global structured instability.

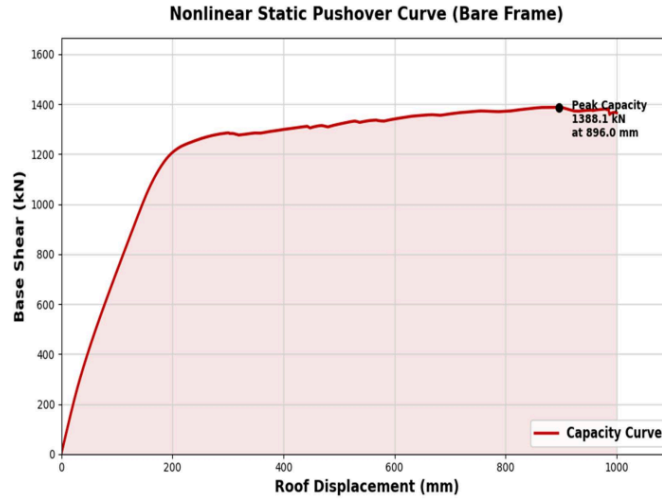


Fig. Pushover Capacity curve of structure

5.3. Time-History Analysis

Before optimization and application of the passive control system, an NLTHA was conducted on the uncontrolled bare frame with the Benchmark Taft 1952 Earthquake record, and the peak uncontrolled roof displacement was determined to be 829.02 mm. When this dynamic seismic demand is compared to the pushover capacity of the bare frame in the inelastic range, the dramatic inelastic response of the uncontrolled frame is noticeable, as the seismic demand will put the structure extremely close to its ultimate lateral capacity. Thus, this clearly demonstrates the urgent need to use an optimized large mass MTMD system in order to dissipate the kinetic energy safely.

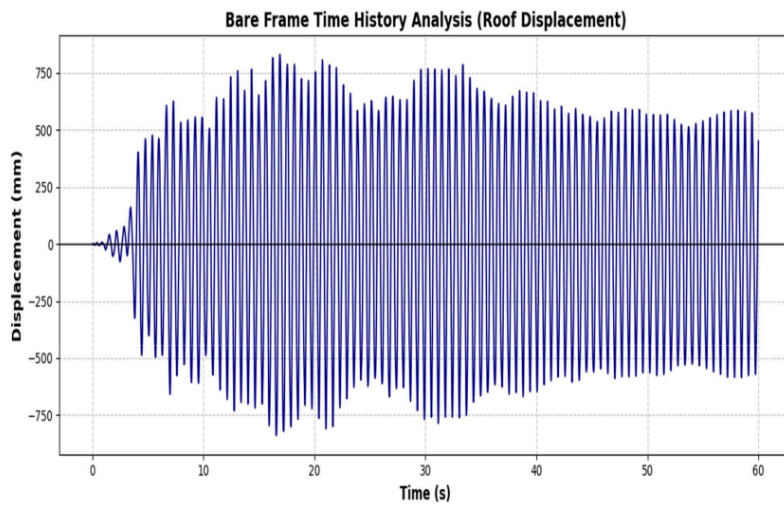


Fig. Bare frame time-history analysis for Taft 1952

5.4. Parametric Optimization Study:

A comprehensive parametric optimization suite was performed directly within the OPENSEESPy framework to find the absolute optimum reduction in response. Numerical procedures automatically adjusts the mass ratio, placement and the necessary mechanical damping ⁵ to minimize the absolute kinematic displacement response of the mainframe structure.

5.5. Mass ratio optimization

²² The mass ratio (μ) is defined as the ratio of the mass added to the frame as the TMD to the total effective mass of the mainframe. It is considered as the most important parameter

that will influence the amount of kinetic energy the MTMD can absorb. The numerical optimization curves for the roof-level installation indicates a steady displacement reduction ⁴⁴ as the mass ratio increases from 1% up to 6%.

The transition from uncontrolled baseline (828.02 mm) to a 6.0% mass ratio yielded the absolute global maximum reduction of 68.27%, dropping the peak roof displacement down to 265.90 mm. Interestingly the data reveals a nonlinear, parabolic efficiency trend, that is increasing the mass ratio beyond 6.0% decreases the control effectiveness. This occurs because excessively heavy damper masses alter the primary structure's natural frequencies too severely, causing a detuning effect where the dampers fall out of optimum phase resonance with the earthquake excitation. Therefore, the 6.0% mass ratio is the global optimum.

Table 2: Effect of mass ratio on structural response control

Target Location	TMD Mass Ratio	Peak Roof Displacement	Peak Reduction (%)
N/A (Bare Frame)	0%	838.02 mm	0.00%
Roof	1%	424.29 mm	49.37%
Roof	3%	338.39 mm	59.62%
Roof	5%	282.08 mm	66.34%
Roof	6% (Global Optimum)	265.90 mm	68.27%
Roof	7%	276.80 mm	66.97%
Roof	9%	315.43 mm	62.36%

Roof	10%	342.25 mm	59.16%
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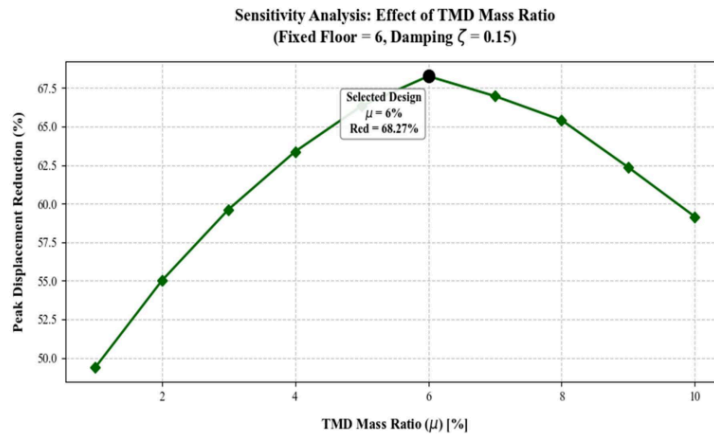


Figure : Sensitivity analysis of TMD mass ratio

5.6. Spatial placement optimization

To confirm the spatial efficiency of the system iteration outputs for the optimum 6.0% TMD mass were systematically evaluated across all floor levels. The fundamental dynamics of structural control dictate that a mass damper is most effective when placed at the point of maximum amplitude of the mode shape it is intended to control.

The control efficacy steadily increases as the dampers are placed higher in the structure. The minimum displacement reduction of 24.94% occurred on floor 1, where the relative modal displacement is smallest. While the maximum displacement reduction of 68.27 % was realized when the TMD was located on floor six. Therefore, the topmost floor (roof)

is quantitatively confirmed as the optimum spatial placement location for mitigating the fundamental mode of vibration.

Table 3: Effect of TMD placement on structural response control

Placement Location	Peak Roof Displacement	Peak Reduction (%)
N/A (Uncontrolled Baseline)	838.02 mm	0.00%
Floor 1 (Inner Nodes)	629.02 mm	24.94%
Floor 3 (Inner Nodes)	370.32 mm	55.81%
Floor 5 (Inner Nodes)	279.81 mm	66.61%
Floor 6 (Inner Nodes - Roof)	265.90 mm	68.27%

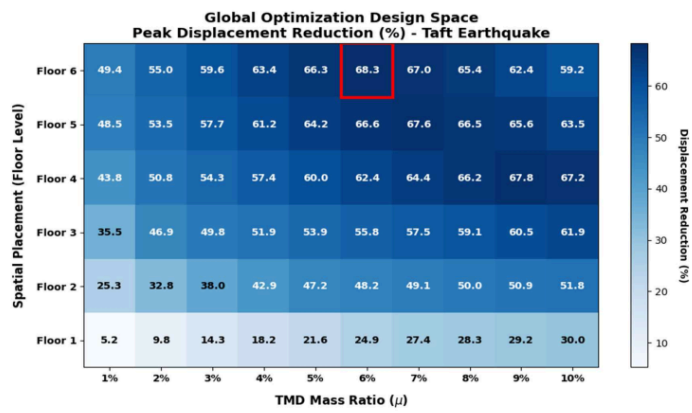


Figure : Global optimization

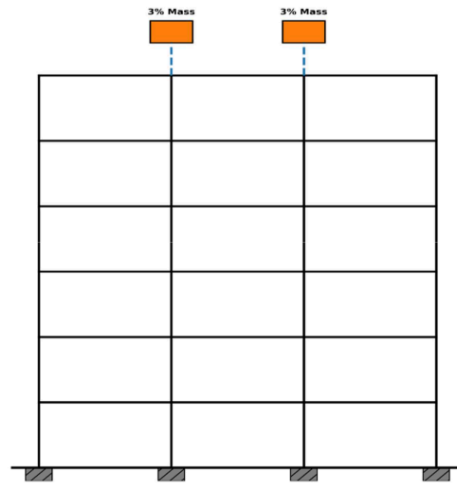


Figure : Placement of TMD on the RC frame

5.7. Mathematical Foundations of Damping Optimization

To rigorously evaluate the damping sincerity of the proposed 6.0% mass ratio TMD system, the optimization must be viewed through the lens of the complex model analysis. For a primary structure equipped with a TMD, the damping matrix is inherently non-proportional, meaning the system cannot be decoupled using classical real modes and is governed by a state-space formulation. Advanced tuning methodologies dictates that the absolute optimum performance is achieved when the frequency and damping ratio yields equal and large modal damping of the first two complex modes of vibration. By tuning to this point of multiplicity, the optimum damping ratio maximizes the power flow of the primary structure's kinetic energy into the viscous dashpot of the TMD.

5.8. High-Resolution Parametric Sensitivity Mapping

Following the identification of the 6.0% global optimum mass ratio located at the roof, a high-resolution sensitivity study was performed to isolate the effect of TMD's mechanical damping ratio (ζ_{opt}) and to evaluate the penalties associated with mistuning. The mechanical damping ratio of the dashpot was systemically varied from 0.020 to 0.350 to numerically map the performance basin of the control system. The analytical data demonstrates that the absolute minimum peak displacement of 265.90 mm is precisely achieved by an optimum damping ratio of $\zeta_{opt} = 0.157$.

Table 4: Effect of damping ratio on response control

Damping Ratio (ζ)	Peak Displacement (mm)	Reduction (%)
0.020	477.23 mm	43.05 %
0.075	299.95 mm	64.21 %
0.157 (Optimum)	265.90 mm	68.27 %
0.254	300.64 mm	64.12 %
0.350	327.75 mm	60.89 %

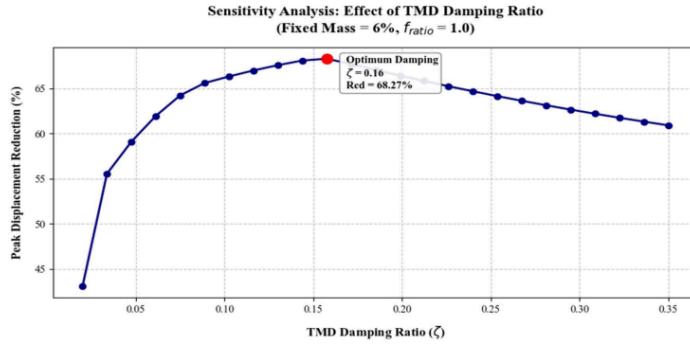


Figure : Sensitivity analysis of damping ratio

5.9. Robustness Against Mechanical and Structural Detuning

The sensitivity analysis explicitly quantifies the robustness of the large-mass configuration against mechanical detuning. Severe under-damping restricts the system's ability to safely dissipate the transferred kinetic energy, dropping the peak reduction significantly down to 43.05%. Conversely, the system is remarkably forgiving to over-damping. Even at an extreme damping ratio of $\zeta = 0.350$, the system still maintains a highly robust 60.89 % peak reduction.

This confirms that the performance basin around the optimum tuning point is a remarkably flat for positive damping deviations. As corroborated by recent literature on large mass ratio TMDs, while the performance function around the minimum point is very steep and sensitive for conventional small TMDs, it became fundamentally flattened for large TMDs. Because the 6.0% mass ratio is relatively large, the required optimum damping ratio ($= 0.157$) is substantially higher than the 1% to 3% damping ratios typically seen in the small-mass setups. This elevated damping effectively widens the frequency suppression bandwidth of the absorber. Consequently, even if the primary structure's

natural frequency degrades due to post-yield stiffness loss during several earthquakes, the flattened frequency response function ensures the TMD remains firmly engaged in out-of-phase resonance.

Table : Sensitivity analysis for determining optimum parameters

Primary Structure Damping (ξ_p)	TMD Mass Ratio (μ)	Optimum Tuning (f_{opt})	Optimum Damping (ξ_{opt})	Peak Response Reduction (%)
5%	1.00%	0.985	0.064	49.37%
5%	2.00%	0.972	0.09	56.17%
5%	3.00%	0.959	0.111	61.47%
5%	4.00%	0.946	0.128	65.25%
5%	5.00%	0.933	0.143	67.51%
5%	6.0% (Optimum)	0.92	0.157	68.27%
5%	7.00%	0.907	0.169	67.70%
5%	8.00%	0.894	0.181	65.99%
5%	9.00%	0.881	0.192	63.15%
5%	10.00%	0.868	0.202	59.17%

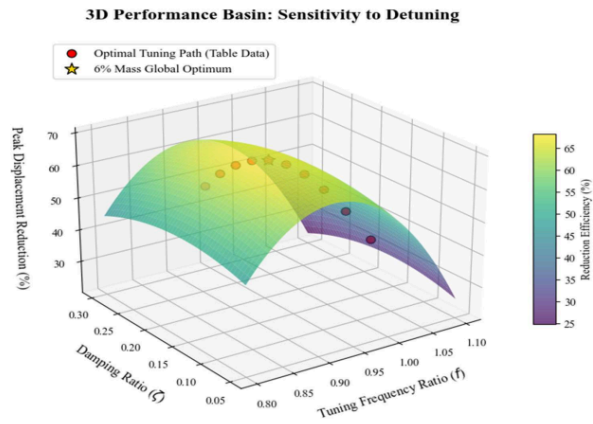


Figure : Heat graph

Now for 6.0% mass ratio and TMD placement at roof optimization of damping ratio and tuning frequency

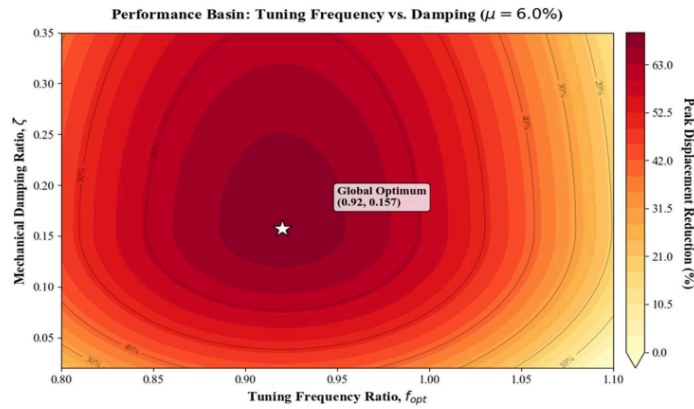


Figure Tuning frequency vs damping

The data in table strongly aligns with explicit closed-form theories for base-excited damped systems. As the mass ratio (μ) increases, the optimum frequency tuning ratio (f_{opt}) demonstrates a distinct, curvilinear decrease, while the optimum damping ratio (ζ_{opt}) non-linearly increases. By softening the restoring springs and stiffness the dashpots at larger mass ratios, the control system successfully locks the frame into its maximum energy-dissipation state.

5.10. Multi-Earthquake Performance Evaluation

To ensure the generalized efficacy of the optimized 6.0% TMD system, non-linear time-history analysis were performed using a expanded suite of unscaled historic ground motions representing highly varied fault mechanisms and frequency contents.

Earthquake Record	Uncontrolled Peak (mm)	Controlled Peak (mm)	Peak Reduction (%)
Ardal (1977)	3177.94	1420.48	55.30%

Denizli (1976)	856.29	686.79	19.79%
El Centro (1940)	1238.03	611.2	50.63%
Kobe (1995)	2072.8	1489.51	28.14%
Lefkada Hospital (1988)	1199.44	903.53	24.67%
Provadja (1983)	738.99	343.78	53.48%
Taft (1952)	838.02	265.94	68.27%
Uttarkashi (1991)	503.92	269.78	46.46%

Under most tested excitations, the TMD system successfully mitigated structural demand, achieving peak roof displacement reductions ranging from a highly measurable 19.79% up to an exceptional 68.27%.

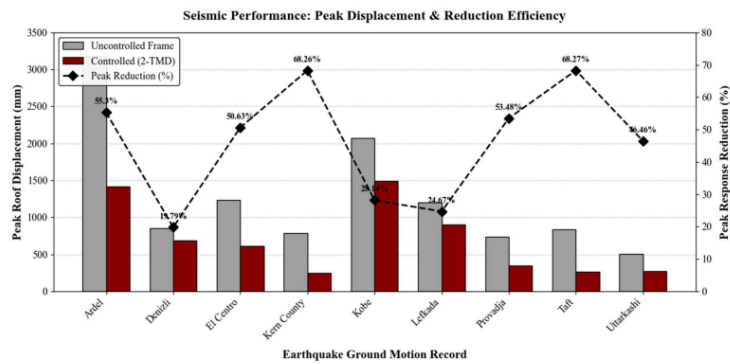


Figure : Reduction efficiency of 2-TMD across various earthquake

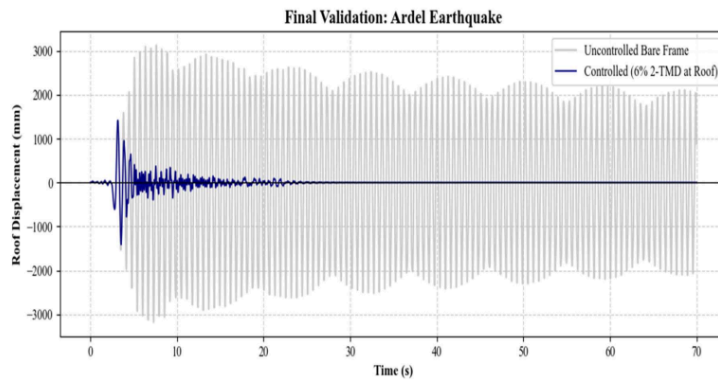


Figure. Displacement vs Time graph for Ardel Earthquake

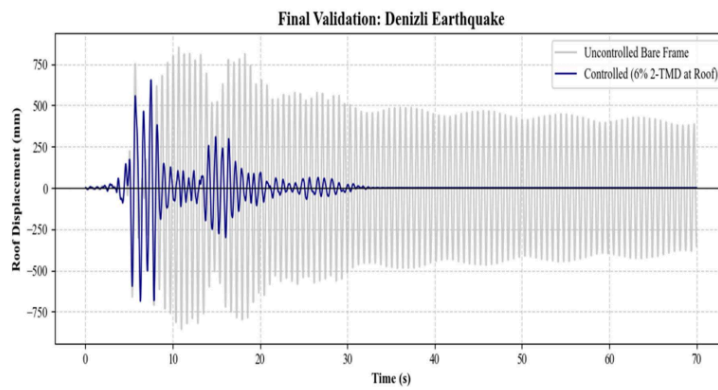


Figure. Displacement vs Time graph for Denizli Earthquake

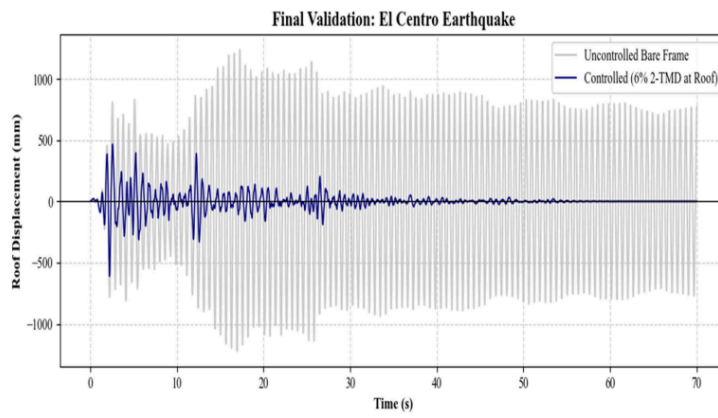


Figure. Displacement vs Time graph for EL Centro earthquake

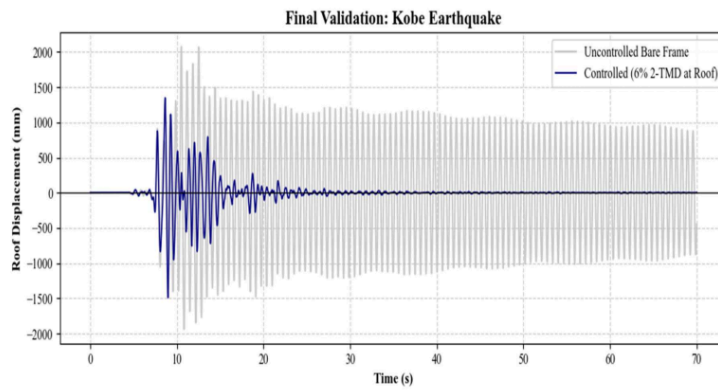


Figure. Displacement vs Time graph for Kobe Earthquake

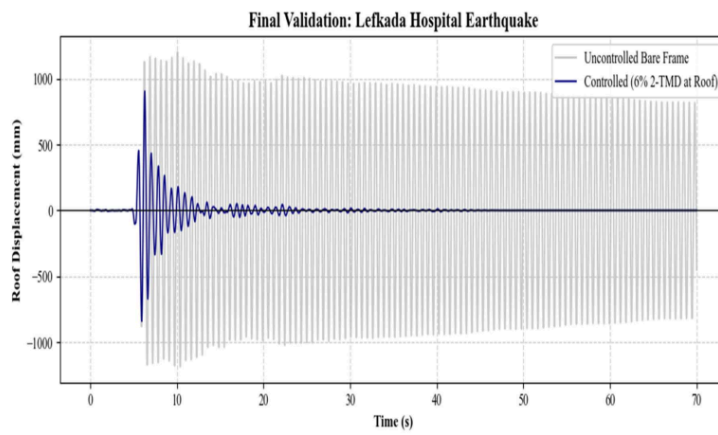


Figure. Displacement vs Time graph for Lefkada Hospital Earthquake

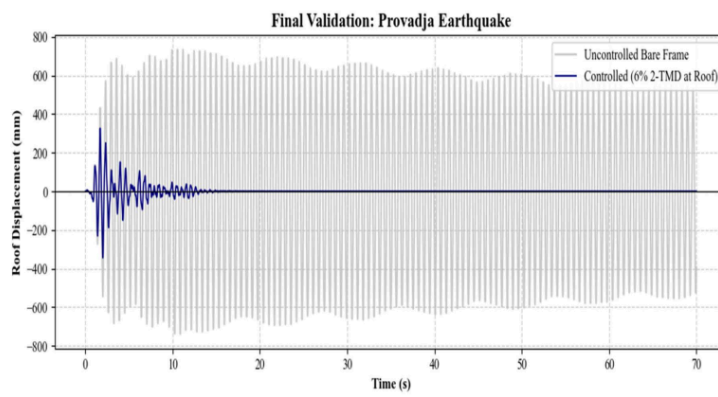


Figure. Displacement vs Time graph for Provadja Earthquake

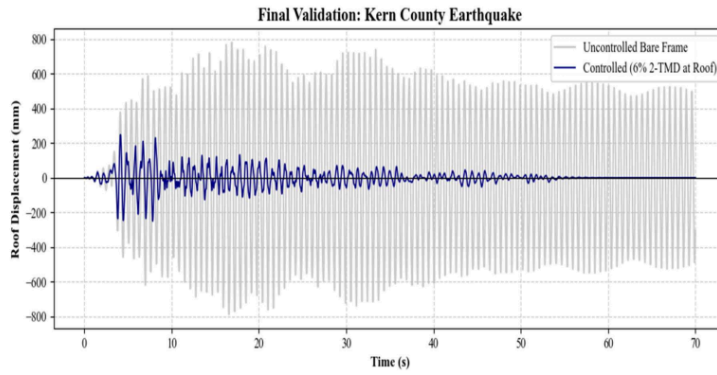


Figure. Displacement vs Time graph for Kern County Earthquake

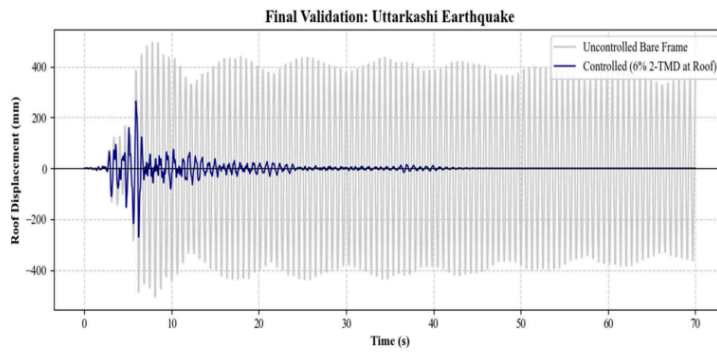


Figure. Displacement vs Time graph for Uttarkashi Earthquake

5.11. Performed Under Far-Field and Broad-Band Excitation

The dampers performed exceptionally well in the Taft (68.27%), Adele (55.30%), Provadja (53.48%) and El Centro (50.63%) earthquake records. This high efficiency is primarily attributed to the sustained frequency content of these far-field, broadband ground motions. Because TMDs operate on the principle of resonance, the sustained dynamic loading provides sufficient time for passive mass dampers to fully mobilize their stroke built-up out-of-phase kinetic energy and apply maximum inertial counter forces against primary structure.

5.12. Performance under Near-Fault and Pulse-Like Excitation

Conversely, the minimum reduction occurred during the Denizli (19.79%), Lefkada Hospital (24.67%), and Kobe (28.14%) earthquakes. This reduction in control efficiency during these events can be explained by their impulsive, near-fault nature. Near-Fault seismic excitations, such as the 1995 Kobe earthquake, are typically characterized by severe, short-duration velocity pulses. The rapid increase in the magnitude of the excitation means that the primary structure reaches its maximum deformation demand before the mass dampers have adequate time to respond and vibrate out-of-phase.

Nevertheless, the consistency in the effective performance⁴ of the TMD with 6% mass ratio and roof placement in reducing displacement across the earthquake assembly provides conclusive evidence of its effectiveness proves the concepts validity.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6. Conclusions

This thesis systematically examines the vibration control efficiency of ¹³Multiple Tuned Mass Dampers system for RC framed multistory structures when earthquake vibrations are induced. After research on the topic of TMD and working on OPENSEES software for analyzing the RC framed structure equipped with it, combined with the parametric study for optimum parameters, we can conclude that:

- High Effectiveness: The 2-TMD system is highly efficient in controlling the seismic response of RC frames, achieving a peak roof displacement reduction of 68.27%.
- Mass Ratio Impact: Mass ratio of 6.0% provides an optimal solution for the trade-off between control efficiency and practicability in roof weight enhancement between vibration control and the practical feasibility of adding weight to the roof. Any increment in mass ratio beyond 6.0% only provides a marginal improvement compared to the increase in base shear demands.
- Excitation Sensitivity: The TMDs are most effective for far-field earthquake motions, compared to near-fault motion with pulse nature.
- Multi-Mode Control: The use of multiple dampers rather than a single unit provides more consistent protection by covering a wider frequency bandwidth, which is critical of RC structures that undergo period elongation as they crack

CHAPTER 7 FUTURE SCOPE

7. Recommendations for future work

In this study we have only studied the 2-TMD configuration for the passive MTMD. However, TMD is a broad topic and involves several other concepts and many more possible configurations to be explored and understood, for optimum implementation in real-life scenarios.

Therefore, the future scope of the work is

- Exploring various combinations of passive TMD and MTMDs with active or ⁴⁶semi-active and hybrid control systems to improve performance.
- The frame model considered for the study is two-dimensional, and further study can be conducted involving a three-dimensional structural model.
- A future study
- Exploring inerter-based systems could achieve equivalent control with significantly less physical mass, potentially reducing the cost of the supplemental system.
- Life-Cycle Cost Analysis: Research into the long-term economic benefits of TMDs, including reduced repair costs after seismic events, would provide further justification for their implementation.

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