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Experimental Study of Vibration Control of Framed Structure Using Various Dampers: A Comprehensive Review

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Abstract: ***Tall buildings are becoming more common within contemporary cities, driven by a need for structures that are cost-effective, sustainable, lightweight, adaptable, and rapid to erect. However, as dampening in buildings declines, the probability of failure due to severe vibrations rises. To solve this difficulty, effective energy dissipation systems are required to reduce the dynamic response of buildings. Several solutions have been developed to reduce vibrations, including passively energy dissipation systems, that allow mechanical devices that gather energy without the need for an external power source. Passive devices release forces in reaction to structural motion, which reduces the building's energy consumption. Metallic dampers, frictional dampers, viscoelastic dampers, & fluid viscosity dampers (FVDs) are all commonly used. FVDs, for particular, are extremely effective at managing shock forces and controlling structural motion. By combining stiffness & damping parts, these devices greatly improve the structure's stability under dynamic loading situations, adding to the safety and robustness of current high-rise structures. This research emphasizes the significance of FVDs as a dependable option for vibration management in tall constructions.***

Keywords: ***Fluid Viscous Dampers (FVDs), Passive Energy Dissipation, Vibration Control, Dynamic Response Mitigation Tall Building Structures etc.***

I. INTRODUCTION

Earthquakes are one of the most devastating natural hazards, affecting life and infrastructure across the globe. With hundreds of small earthquakes occurring daily and major events causing significant destruction, their impact on human lives and property is profound. The damage caused by earthquakes is primarily concentrated on man-made structures, which often fail under the intense seismic forces, leading to loss of life and economic setbacks. This worrying circumstance has forced the creation of earthquake-resistant buildings in order to reduce hazards and secure the safety of residents. In this setting, earthquake engineering has arisen as a critical field in civil engineering, focusing on designing structures that can endure seismic forces effectively [1].

The urbanization and growing population of modern cultures have led to an extraordinary increase in the building of high-rise buildings. These structures are increasingly being built to optimize land use in densely populated urban areas. However, their behavior under dynamic forces, such as earthquakes and wind, is a critical concern. Seismic loads, primarily a function of a structure's self-weight, and wind loads, which result from airflow pressure, are among the most significant challenges faced by structural engineers. While lightweight materials and designs offer economic advantages, they often lead to low natural damping, making buildings more susceptible to vibrations during earthquakes and high winds. The vibrations induced by seismic activity can cause significant discomfort and danger to building occupants. Natural damping in structures typically averages around 5% of critical damping, which is insufficient to counteract the effects of strong dynamic forces. This highlights the need for advanced strategies to control vibrations and ensure the structural integrity of high-rise buildings. To achieve this, modern buildings are equipped with vibration control devices that dissipate energy imposed by external forces. These devices, chosen based on factors like cost, efficiency, and maintenance requirements, have become an integral part of earthquake-resistant design. Passive dispersion of energy systems are popular vibration control devices due to their dependability and low cost. These systems operate without the need for external power and are actuated by the structure's own motion. One of the most well-known passive cooling systems is the set Mass Damper (TMD), composed of a mass, an elastic spring, and a damping device set to the building's frequency of choice. The TMD collects vibrational energy, minimizing the building's reactivity to seismic and wind pressures.

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Another effective solution is the viscous fluid damper, It employs an incompressible fluid inside a cylinder to waste energy through the rotation of a piston. These dampers transfer forces and reduce deformation demands, significantly improving the structure's performance under dynamic loading.

The integration of such systems in modern construction not only enhances safety but ensures that high-rise buildings be resilient in the event of natural disasters. By focusing on advanced damping technologies, engineers can design structures that meet the stringent demands of earthquake-resistant construction while maintaining economic and functional efficiency. This paper explores the role of vibration control devices, particularly TMDs and viscous fluid dampers, in mitigating seismic and wind-induced loads, offering a comprehensive understanding of their importance in contemporary structural engineering.

II. PROBLEM STATEMENTS

1) Increasing Urbanization: The construction of tall buildings and framed structures is on the rise due to growing urban populations and the demand for high-rise developments.
2) Vibration Vulnerability: These structures are prone to vibrations induced by dynamic forces such as earthquakes, wind, and human activity, leading to discomfort and potential structural instability.
3) Lightweight Design and Low Damping: Modern building materials and techniques prioritize cost-effectiveness, resulting in lighter structures with low inherent damping, making them more susceptible to excessive vibrations.
4) Impact of Dynamic Loads: The lack of adequate vibration control in lightweight structures can lead to significant deformations, risking structural integrity and occupant safety, especially during seismic events and strong winds.
5) Role of Passive Control Systems: To address these issues, passive control systems, particularly Fluid Viscous Dampers (FVDs) and Tuned Mass Dampers (TMDs), are increasingly integrated into framed structures to mitigate vibrations.
6) Challenges in Selection and Optimization: Choosing the appropriate damping system and optimizing its placement involves balancing factors like damping type, efficiency, cost, weight, and maintenance requirements with the building's design specifications.
7) Objective: The goal is to enhance stability, safety, and comfort by minimizing vibrations and extending the lifespan of framed structures, while also maintaining economic feasibility.

III. LITERATURE REVIEW

A. *Literature Survey*

The field of vibration control in civil engineering, particularly in structures subjected to seismic forces, has witnessed considerable advancements in recent years. Various damping systems, ranging from passive to active and semi-active systems, have been investigated to reduce the impacts of seismic excitation. These technologies seek to improve the security, stability, and efficiency of buildings, particularly in earthquake-prone areas. The literature reveals a variety of approaches, each tailored to specific types of structures and seismic conditions.

Liu, Wang, and Fang (2022) A study was undertaken on seismic vibrations control in prefab steel frames with momentary resistance (MRF) using a tuned mass damper. They conducted shaking table tests using three structural models: an uncontrolled MRF, an MRF using undamped TMD, and an MRF with damped TMD. Their results revealed the fact that damped TMD considerably lowered the structure's peak acceleration, reducing the vibrations by up to 58.69%. This was attributed to the enhanced energy dissipation capabilities of the damped TMD, highlighting its effectiveness in controlling seismic vibrations. The study also emphasized the importance of TMD optimization for further improving the system's performance.

Similarly, Bhowmik and Debnath (2024) Magnetorheological (MR) dampers were employed to provide semi-active vibration control in soft-story buildings. They used the The linear Quantitative Gaussian (LQG) system of control to adjust the damping force. Their findings demonstrated the use of the LQG-based semi-active system of controls lowered the building's peak reaction by more than 67% across several earthquake scenarios, proving MR dampers' ability to protect susceptible soft-storey structures with little effort. The study also compared the performance of the LQG control to the classic proportional-integral-derivative (PID) control, emphasizing the superior performance of LQG in terms of response reduction.

Mousaviyan Safakhaneh et al. (2024) An active tunable mass damper (ATMD) was introduced to regulate the tremors of a ten-story structure during an earthquake. The ATMD system combines a mass, spring, a damper, and actuator to provide superior structural damping. The paper presented a new control method based on the building's dynamic response and ATMD rigidity, which was tested against linear-quadratic regulator (LQR) or fuzzy logic controller (FLC) methods. The results revealed a reduction in movement et acceleration responses of 40% and 28.16%, accordingly, compared to the unmanaged system, showcasing the effectiveness of ATMD and the proposed control strategy.

Lu et al. (2024) We investigated a semi-active hit damper (SAID) in multi-modal vibration management of structures during earthquakes. The SAID system, which relies on a vibro-impact system, underwent testing on a five-story framing building. The system's damping performance was found to be efficient at transferring structure vibration energy into higher modes, resulting in faster energy dissipation and a lower structural response. The SAID system produced over 40% attenuation on the root-mean-square structure response, demonstrating its promise as a dependable semi-active vibration management system for earthquake protection.

Li, Li, and Bi (2022) A new quasi-active negative rigidity damper (QANSD) has been designed for controlling structural vibration under seismic forces. The QANSD blends a negative rigidity element and an adjustable damping element to provide active performance control with much lower energy usage. The study evaluated the responses of the QANSD technology to passive, active, or semi-active control methods. The results demonstrated that the QANSD system achieved similar performance to active control systems, effectively mitigating inter-storey drift, displacement, acceleration, and structural shear with reduced energy requirements.

Wang et al. (2021) A spring pendulum hammering tuned masses damper (SPPTMD) was tested for noise reduction in high-rise constructions. The SPPTMD technology is based on internal resonance & energy dissipation through impact, showed significant vibration reduction, especially in tall and slender structures subjected to strong seismic actions. The numerical analysis revealed that the SPPTMD system outperformed the spring pendulum, making it a promising solution for high-rise buildings prone to violent vibrations.

Bathaei and Zahrai (2024) focused on a hybrid vibration control system combining tuned mass dampers (TMDs) and magnetorheological (MR) dampers, using model predictive control (MAC) to address time delays in control systems. Their study on an 11-story structure demonstrated that the MAC control system effectively compensated for time delays and outperformed traditional fuzzy logic and passive control systems, achieving improvements in displacement and base shear reduction by up to 11.8% and 8.32%, respectively.

Friis et al. (2021) investigated two-level friction damping for vibration control in high-rise buildings. This innovative approach involves the use of friction dampers, which provide a cost-effective and reliable means of mitigating vibrations across different deformation modes. Their research highlighted the potential of friction dampers for Multifunctional vibration control for high-rise structures, particularly as buildings become higher and more slender.

B. Gap Identified

While research on multiple tuned mass dampers (MTMD) has demonstrated their effectiveness in enhancing structural performance against dynamic loads, several gaps remain in the existing literature. Despite the advancements in non-uniform distribution strategies for MTMDs, there is a lack of comprehensive studies exploring the optimal configurations for multi-story or complex structures. Most research focuses on systems with a single degree of freedom, leaving the behavior of MTMDs in higher-dimensional systems under various dynamic loads less explored. Additionally, while advanced analytical methods like the reverberation matrix method (RMM) have proven beneficial, there is limited exploration of their applicability in real-world, large-scale structures with varying damping and mass distributions. Moreover, The impact of outside conditions, such as heat and age effects, on damper function is sometimes underestimated. Finally, although innovations like series-connected TMDs show promise, further investigations into their long-term reliability and cost-effectiveness in practical applications are needed. These gaps provide opportunities for further research and optimization of MTMD systems.

C. Summary of Literature

The literature on multi tuned mass damping (MTMD) demonstrates their usefulness in decreasing structural vibrations caused by changing loads such as wind and seismic forces, and harmonic excitations. Early studies by Frahm and Hartog laid the foundation for TMD design, with subsequent research emphasizing the limitations of single TMDs, particularly their sensitivity to frequency mistuning. Multiple dampers with varying dynamic characteristics have proven more effective, as evidenced Iwanami and Seto showed that the two TMDs outperform a single one. Various studies, including those by Clark, Joshi, and Jangid, optimized MTMD configurations to reduce structural motion. Research on the number, mass distribution, and damping ratios of MTMDs revealed that non-uniformly distributed systems, including linearly distributed ones, often perform better. Studies also explored the role of MTMDs in mitigating seismic responses and dynamic magnification, with results showing significant reductions in building accelerations and structural vibrations, underscoring the potential of MTMDs in enhancing structural stability.

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IV. COMPARATIVE ANALYSIS

A. *Comparison of key studies and findings:*

Several studies have focused on vibration control in seismic protection, each offering valuable insights into different methods and strategies. The key findings of these studies can be grouped based on the type of damping system, control algorithm, and structural considerations.

Vibration Control Systems: A key trend in the reviewed papers is the investigation of passive, semi-active, or active vibration systems for control. Traditional passive damping technologies, such as viscoelastic damper & tuned mass damping (TMD), have been well researched for their capacity to minimize seismic responses in structures. For example, passive dampers were discovered to be effective in lowering displacement and velocity, but their effectiveness is often limited by the need for optimal design parameters and material properties.

Quasi-Active Negative Stiffness Dampers (QANSD): Studies on QANSD highlight their potential in enhancing damping performance in dynamic systems. These systems offer increased energy dissipation capabilities and higher stiffness during seismic events, improving structural stability. They also demonstrate better adaptability compared to traditional passive systems in structures experiencing variable loads. However, their real-world applications and long-term performance in diverse conditions are still under-researched.

Semi-Active and Impact Dampers: Research into semi-active dampers and impact-based dampers (SAID) shows that they provide better flexibility and control under varying seismic conditions. These systems are more responsive to changes in loading conditions and can offer improved performance when combined using modern control techniques.

The linear approach Quadratic Gaussian (LQG) with MPC (Model Predictive Control) algorithms are commonly used in the evaluated studies. They aim to reduce the structural response by adjusting the control forces dynamically. While LQG control is known for its simplicity and efficiency, MPC is more suited for large-scale, multi-modal systems. The integration of these control strategies with advanced materials such as shape memory alloys (SMA) and piezoelectric actuators has shown promising results, particularly in reducing energy consumption and enhancing response time during seismic events.

Software Application: Studies like those by Arghya Ghosh (2022) and Er. Sanjeev Kumar (2016) highlight the growing dependence on STAAD Pro for reviewing structural designs, bringing insights on the benefits of automated validation of designs on both steel & truss structures.

B. *Evaluation of methodologies used in the reviewed studies*

1) *Structural Analysis Techniques:* Structural analysis is a crucial part of the vibration control process, and the methodologies used vary greatly among the studies. A common approach in most studies is Using finite element analysis, or FEA, to model structures and simulate seismic loading scenarios. This allows for detailed insights into stress distribution, displacement, and the effectiveness of damping systems.

- Dynamic Analysis: Studies typically rely on dynamic analysis techniques such as Damping systems' performance can be evaluated using time-history analysis, spectrum response evaluation, and modal analysis. Period-history analysis offers a more realistic portrayal of seismic reaction across time, it is computationally expensive. Response spectrum analysis is simpler but may not capture all the nuances of complex seismic events.
- Numerical approaches, such as a Newmark-beta or Runge-Kutta method, are used in research to simulate seismic loads on damped buildings. These techniques are critical for evaluating the efficacy of management algorithms and testing the efficiency of damping systems in various settings.
- Multi-Modal Vibration Control: Fewer studies explore multi-modal vibration control techniques, which are essential for complex, multi-storey buildings or high-rise structures. Multi-modal approaches are crucial as they account for the interaction of multiple vibration modes, which is especially important for buildings with non-linear dynamic behavior.

2) *Control System Integration:* The integration of control systems such as LQG and MPC is another key area of research. The studies typically implement these algorithms on simplified models or small-scale systems before scaling them up for larger, more complex structures. While this provides valuable insights, a gap exists in terms of real-world application, particularly regarding the ability to address system delays, non-linearities, and uncertainties in seismic loading.

C. Highlighting trends, advancements, and challenges

1) Trends and Advancements

Smart Materials: The incorporation of smart materials such as shape memory alloys and piezoelectric actuators has gained attention in recent studies. These materials offer significant advantages in terms of adaptiveness and energy efficiency, making them a promising option for future vibration control systems.

Hybrid vibration management systems, which combine both active and passive dampers, are a growing trend. These types of systems have been created to take use of both the simplicity of passive systems and the adaptability of active systems.

Real-Time Control: The development of real-time control systems that can adjust damping forces based on seismic intensity is a key advancement. These systems are capable of responding dynamically to varying seismic conditions, improving performance during large seismic events.

2) Challenges

Implementation in Complex Structures: One of the major challenges identified in the studies is the limited application of advanced vibration control systems to complex structures, particularly high-rise buildings and buildings with irregular geometries. These structures often exhibit more complex dynamic behaviors that are difficult to model accurately.

Cost and Maintenance: The integration of advanced damping systems and control algorithms adds complexity and cost to the construction and maintenance of buildings. Furthermore, ensuring the reliability of these systems over long periods, especially under varying seismic intensities, remains a challenge.

While significant advancements have been made in vibration control for seismic protection, there remain challenges related to system integration, material development, and real-world application. The ongoing development of hybrid systems, smart materials, and real-time control algorithms promises to address some of these issues in the near future.

Authors/Year	Methods/Key Findings	Limitations/Research Gap
Liu, X., Wang, W., & Fang, C. (2022)	Full-scale shaking table test; Damped TMD reduces peak acceleration by 50.23%-58.69%	Further optimization of TMD design needed for various seismic conditions.
Bhowmik, K., & Debnath, N. (2024)	Semi-active vibration control with MR dampers; LQG control reduced peak response by 67%-78%	Performance of LQG compared to other control strategies.
Mousaviyan Safakhaneh et al. (2024)	Active TMD with new control algorithm; Reduced displacement and acceleration by 40% and 28.16%, respectively	Need for real-time application of control algorithms in large structures.
Lu, Z., Zhou, M., Zhang, J. et al. (2024)	Semi-active impact damper (SAID) for multi-modal control; 40% RMS response attenuation	Limited to five-story structure; needs testing on higher buildings.
Li, H., Li, J., & Bi, K. (2022)	Quasi-active negative stiffness damper (QANSD) offers active control performance with less energy	Further study on real-world applications and energy efficiency.
Wang, Q., Li, H. N., & Zhang, P. (2021)	Spring pendulum pounding TMD for high-rise structures; Effective vibration reduction in slender structures	Requires validation for other building types and seismic conditions.
Bathaei, A., & Zahrai, S. M. (2024)	Hybrid MR and TMD dampers with MAC control; Reduced displacement by 11.8% in nonlinear structures	Time delay impact needs further exploration in large-scale systems.
Friis, T., Katsanos, E. I., et al. (2021)	Two-level friction damping for multi-functional vibration control in high-rise buildings	Exploration of additional damping technologies for larger structures.

A variety of vibration control methods and systems designed to mitigate seismic forces, with each system showing potential for application in specific building types. However, further research is required to optimize these systems and address gaps such as real-world applications, energy efficiency, and system scalability.

V. DISCUSSION

A. *Synthesis of findings from literature*

The literature reveals significant advancements in seismic vibration control, particularly through Tuned Mass Dampers (TMDs) and Magnetorheological (MR) dampers. TMDs, particularly when damped, effectively reduce peak accelerations and enhance structural stability during seismic events. Semi-active MR dampers, controlled via Linear Quadratic Gaussian (LQG) frameworks, have shown substantial reduction in peak and root-mean-square responses with minimal energy input. Despite these advancements, limitations such as scalability, cost-effectiveness, Real-world applicability remains. Future study should focus upon optimizing these structures for the vast scale, real-world applications, incorporating smart technologies for dynamic, adaptive performance under varying seismic conditions.

B. *Implications for Study*

Good seismic system should be laterally stiff and laterally strengthened to withstand even low intensity of ground shaking without getting damaged, and should be maintained good vertical strength to withstand gravity loading and to prevent strong earthquake shaking. In traditional approaches,, to achieve capacity (to resistance to be developed with in the structure to oppose severe damages) We should boost elastic toughness or else retain ductility. This increases floor accelerations and damages structural components. In base isolation, instead of expanding capacity, we reduce demand because the structure's strength cannot be increased indefinitely. Because earthquakes are unable to predicted or regulated, we adjust demand by reducing the effects of the base on the superstructure. Seismic dampers replace structural features such as diagonal braces to control earthquakes in structures. It partially absorbs seismic energy and lessens the motion of buildings.

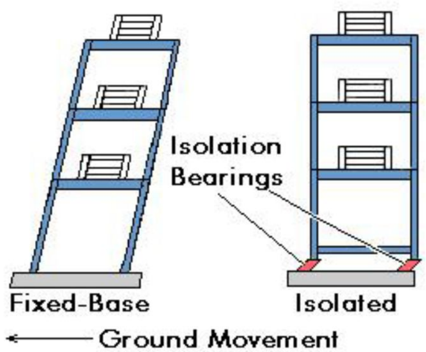

Figure 1. Building with and without isolators at the base

C. *Providing Dampers*

Typically, dampers are massive concrete blocks and steel bodies put in skyscrapers or other buildings and moved in opposition to the structure's resonance frequency oscillations using springs, fluid, or pendulum. Sources of vibrations and resonance. Unwanted vibration can be created by external forces acting on a building, such as wind and earthquake, as well as a seemingly innocuous vibrating source creating resonance, which can be harmful, uncomfortable, or simply bothersome.

An earthquake's seismic waves induce structures to swing and oscillate in a variety of ways, depending on the rate and direction the ground motion, as well as the building's height and construction. Seismic activity might produce excessive vibrations in the building, perhaps leading to structural failure. To improve the building's seismic resilience, an appropriate building design is implemented, which incorporates various seismic tremor control methods. As previously stated, dampening devices were utilized in the aviation and auto sectors long before they became common for reducing seismic damage to structures. The first specialized dampening devices for earthquake didn't arrive until late 1950. Mechanical human sources. Dampers above the Millennium Gate in London. The white disc is not a component of the damper. Masses of individuals walking through the stairs at the same time, or a big number of people stomping together, can cause major problems in big buildings such as stadiums if dampening devices are not installed. Wind Wind can cause the tops of buildings to move by over a meter. This motion can take the form of swinging or bending, causing the upper levels of such structures to shift. Certain wind angles and a building's aerodynamic features can intensify movement and create motion sickness in people.

Figure 2. Structure provided with damper

D. Buildings with and without Dampers

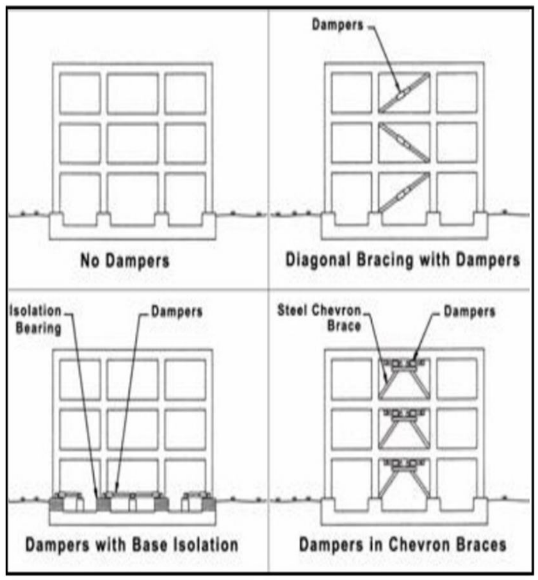

Figure 3. Placement of dampers

Buildings with and without dampers exhibit significant differences in their ability to withstand dynamic forces such as wind, earthquakes, or vibrations. Dampers are devices inserted within an object that soak up and release energy, thereby minimizing the impact of those forces on the structure's stability.

Buildings with dampers: Dampers are commonly used in the design building buildings in susceptible to earthquakes or high-wind locations to increase structural resilience. They can take many different forms, including dampers that are viscous, tuned mass dampers, and friction dampeners, and are intended to absorb movement and minimize vibrations. Dampers help limit structural damage, reduce discomfort resulting from building wobble, and increase occupant safety. Buildings with dampers can often be taller and more flexible while maintaining comfort and safety levels.

Buildings without Dampers: Without dampers, buildings rely solely on their natural stiffness and strength to resist external forces. While this may work for low-rise structures or those in less seismic or windy areas, taller or more flexible buildings can experience significant sway or vibrations, which may lead to discomfort for occupants or even structural damage over time. These buildings may require heavier and more rigid structural elements to maintain stability, which can increase construction costs.

Buildings with dampers offer enhanced safety, comfort, and durability, especially in challenging environments, whereas buildings without dampers may face limitations in performance under dynamic loads.

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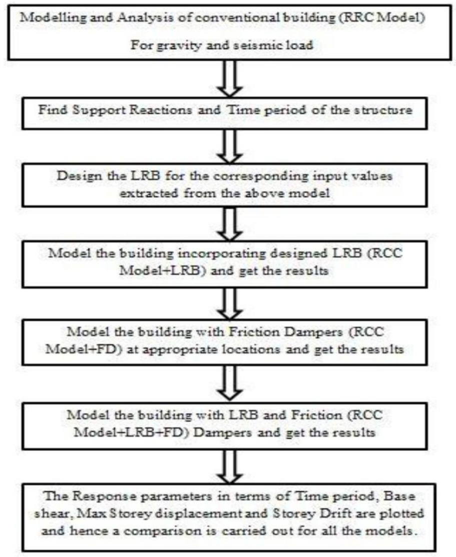

Figure 4. Flow chart of methodology

E. Methodology for future research directions

Future research on seismic vibration control should focus on optimizing and integrating advanced damping technologies for large-scale, real-world applications. A multi-step approach is recommended:

1) Advanced Simulation Models: Develop detailed, nonlinear dynamic models for buildings equipped with multiple dampers, considering both linear and nonlinear seismic forces. Simulations should account for various ground motions and real-world structural behavior.
2) Smart Materials Integration: Incorporate smart materials such as magnetorheological and electrorheological dampers that offer adaptability to changing seismic conditions, using real-time data feedback for dynamic control.
3) Hybrid Systems: Combining passive, semi-active, or active damping approaches creates hybrid systems able to altering damping pressure based on actual time structural behavior or seismic activity.
4) Experimental Validation: Conduct large-scale shaking table tests and field studies on high-rise buildings and complex structures to evaluate the performance of these systems under varying seismic intensities.
5) Optimization Algorithms: Utilize AI-based optimization algorithms for real-time adjustment of damping parameters to maximize efficiency and reduce energy consumption in vibration control systems.

F. Scope and Limitation :

Scope

- Analyse the behaviour of dampers that use fluid for energy dissipation.
- Explore dampers that rely on friction between surfaces to absorb energy.
- UHPFRC is ideal to strengthen and provide corrosion protection for aging beams ,piers ,and abutments.
- Investigate systems that use mass to counter act vibrations, such as tuned mass dampers.
- Study technologies that decouple structures from ground motion, particularly in seismic applications.

Limitations:

- Wear And Tear: Over Time, Dampers Can Degrade Due to Fatigue, Leading to Reduced Performance and Potential Failure.
- Nonlinear Behavior: Some Dampers Exhibit Nonlinear Behaviour Under Different Loading Conditions, Making It Challenging to Predict Their Performance Accurately.
- Cost: Advanced Dampers Can Be Expensive to Manufacture and Maintain, Which May Limit Their Use in Budget Sensitive Projects.

VI. CONCLUSION

Current developments in the construction sector demand taller and lighter buildings that are also more adaptable and have a low damping value. This raises the possibility of failure and causes challenges in terms of serviceability. There are several approaches available today to reduce structural vibration, one of which is the use of TMD. The purpose of this study is to determine the efficacy of employing TMD to control structural vibration. A numerical approach was created to simulate the multi-story, multi-degree freedom structure frame structure as a shear structure with a TMD. Another numerical approach is designed to analyze the 2D-MDOF frame architecture fitted with a TMD. The current study focuses on TMD's capacity to reduce structural vibration caused by an earthquake. A single and double story frame model are tested experimentally without or with TMD to assess structural reaction, and the results are provided in graphical & tabular formats. TMD was used to investigate the effect of different variables on the amplitude response, including frequency ratio, ratio of mass, and damping ratio.

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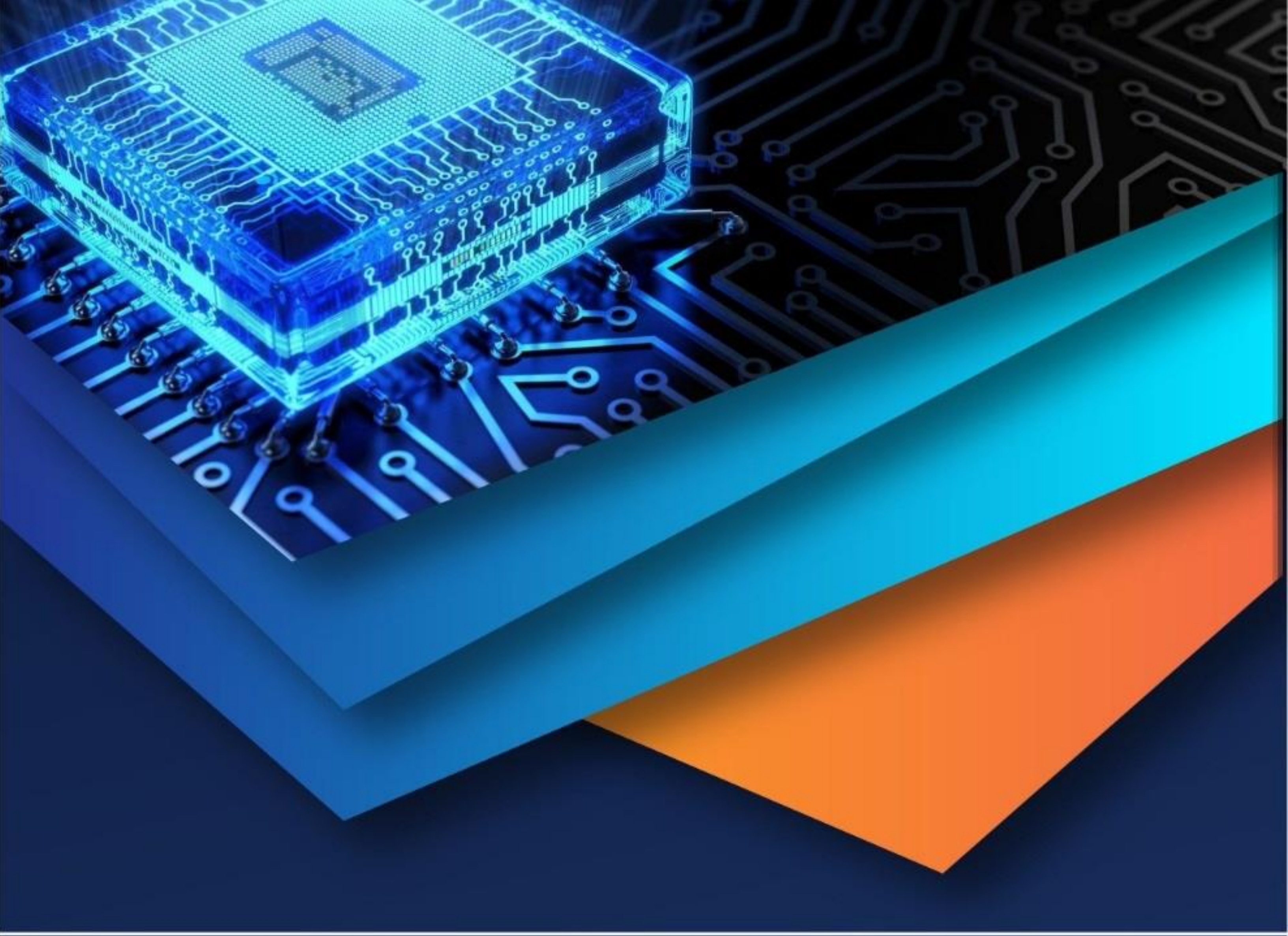

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