World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Research Article)

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Analysis and design of high-rise steel buildings with semi-active dampers

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World Journal of Advanced Engineering Technology and Sciences, 2026, 20(02), 016–029

Publication history: Received on 22 June 2026; revised on 29 July 2026; accepted on 31 July 2026

Article DOI: https://doi.org/10.30574/wjaets.2026.20.2.0384

Abstract

The growing need of the high-rise steel buildings in the fast-developing urban areas has led to the introduction of the new and improved structural control systems that focus on the safety, serviceability and comfort of occupants during the dynamic loading conditions. Such structures are easily vulnerable to vibrations and seismic forces caused by the wind and can result in uncontrolled movement, inter-storey drift and structural damage due to their slenderness and flexibility. This paper provides a detailed literature review on semi-active damping system and how this system can be used in the analysis and design of high-rise steel structures. This paper summarizes the results of recent studies on fluid viscous dampers, tuned mass dampers, magnetorheological dampers, and hybrid control systems. The focus is on semi-active tuned mass dampers (SATMDs), which have adaptive performance, as they modify the damping properties on-the-fly with minimal energy use. The review shows that optimization techniques, control algorithms, and soil-structure interaction are important in improving the efficiency of the damper. Comparative studies reveal that semi-active systems are more effective than the traditional passive devices in damping vibration, displacement, and acceleration, and more robust to the current circumstances of diverse loads. In addition, life-cycle cost analysis shows that such systems are economically and structurally beneficial in the long run even though they are more expensive to purchase. On the whole, semi-active dampers integration is a major contribution to the current structural engineering, which adds to the resilience and sustainability of tall buildings design along with high performance.

Keywords: High-rise steel buildings; Semi-active dampers; Structural control systems; Tuned mass dampers; Seismic response; Wind vibration; Soil–structure interaction; Life-cycle cost analysis

1. Introduction

The unprecedented growth of urbanization in the world has resulted in a significant rise in the need of high-rise steel structures, especially where land availability, commercial growth, and modernization of infrastructures are the key determinants of planning activities (Pawar & Salgar, 2026). Tall buildings have been constructed with steel due to its high strength to weight ratio, ductility, quick construction and allows flexible architectural planning. Yet, the very traits that make steel an attractive material to use in high-rise construction also make these structures more sensitive to dynamism. In modern tall buildings, it is common to have slender, lightweight, and material-efficient tall buildings, which minimize dead load but make them more vulnerable to lateral movements when excited by winds and earthquakes (Demetriou et al., 2016). So, for very tall steel buildings, design should not only consider strength and stability, but also serviceability aspects including inter-storey drift, floor acceleration, vibration perception and fatigue. Vibration loads (caused by wind, earthquakes, people and vehicles) can cause excessive vibration that may have a detrimental effect on the structure, the façade, the non-structural elements and human comfort (Wang et al., 2024a). These issues have led structural engineers to look for innovative vibration mitigation techniques that are beyond traditional strengthening techniques. Therefore, structural control systems have become a prominent research topic for the analysis and design of tall buildings, particularly in seismic and wind-prone regions where it is critical to consider resilience and adaptability in design

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Of the various technologies, damping systems have gained particular attention because they enhance building performance by affecting the dissipation of a fraction of the input energy in the system (Almajhali, 2023). Fluid viscous dampers, tuned mass dampers, buckling-restrained braces and hybrid control devices have been extensively studied in recent years for application in high-rise buildings. Fluid viscous dampers provide a good solution because they produce a velocity-dependent resisting force and can reduce wind- and earthquake-induced Responses

(Almajhali, 2023). In contrast, tuned mass dampers work by providing an additional mass-spring-damper system that is mounted on the building structure, typically at the top, with its natural frequency tuned to that of the primary structure. This allows the device to counteract the structural vibration and absorb energy. Passive tuned mass dampers are appreciated for their simplicity, effectiveness and relatively low cost of operation, but they tend to be effective in a relatively narrow frequency band. As high-rise steel structures may have variable loading and even altered dynamic properties under extreme events, passive control strategies can not always provide optimum efficiency. This has prompted the emergence of semi-active, active and hybrid damping systems, which aim to offer greater flexibility and response control under uncertain and changing loading conditions (Lee & Oh, 2025). The move from passive to semi-active elements is an important step in smart building design, especially for steel high-rise buildings, where adaptability is key.

Semi-active dampers are particularly suitable for high-rise steel-framed buildings as they provide a viable compromise between the control efficiency, energy consumption and reliability (El Ouni et al., 2022). Semi-active devices can adaptively change certain mechanical properties (such as damping or stiffness) of the system in response to the actual structural response, in contrast with passive devices. Semi-active systems typically include sensors, a controller, and an adaptive damping or stiffness device that can vary its performance based on a specified optimisation strategy. This feature allows the system to adapt to variations in wind forces, seismic pulses and the building's vibration properties. Semi-active devices have a lower energy demand than fully active devices because they do not introduce large control forces into the building; rather, they control system parameters to dissipate energy (Ai et al., 2025). The research has shown that under certain circumstances, semi-active systems can successfully overcome the limitations of passive control systems and may perform as well as active systems. It has also been suggested that stiffness variation is generally more effective than damping variation in tuned systems, as it assists in maintaining instantaneous frequency tuning while excessive damping variations may kill the frequency tuning effect. This is a key observation for high-rise steel buildings as it is important to ensure that a damper's characteristics remain compatible with the structure's dynamic behaviour to ensure reliable performance under multiple hazards.

The existing literature on structural control shows that the design of damping systems has progressed from simple conceptual ideas to advanced control strategies with computational analysis, optimisation and full-scale implementation (Tan et al., 2025). A thorough review of 27 research articles, along with review studies presented in the field, shows researchers have investigated a wide variety of concerns such as wind response of tall buildings, seismic performance of irregular buildings, effectiveness of various damping devices and retrofitting measures for existing buildings (Al-Subaihawi et al., 2020). Recent research has also stressed the need for using metaheuristic optimization to find the optimal damper placement, as the placement and arrangement of dampers significantly impact the effectiveness of displacement, acceleration and drift reduction. This is particularly important in the case of irregular or asymmetrical tall steel buildings due to torsional and higher mode response (Zuo et al., 2023). Various simple approaches have been suggested to retrofit existing buildings with additional damping devices without having to replace the entire structure to enhance building safety and serviceability. Recent studies comparing the effectiveness of fluid viscous dampers, buckling-restrained braces, tuned mass dampers, and hybrid systems generally reveal that no one device is the best for all conditions, and that the optimal device selection depends on several factors, including building height, structural irregularity, hazard type, control objective, available power, and cost. Therefore, the design of high-rise steel buildings with semi-active dampers should be considered a structural-control issue rather than a simple dampers-installation problem.

A further major advance of recent research has been to consider the response mitigation effects of damping systems, but also their performance and economic effects over the life-cycle of the structure. While semi-active and other advanced damping systems may be more costly to install than traditional measures for structural strengthening, life-cycle cost analysis has demonstrated that the long-term savings can justify the initial cost (Sanati & Karamodin, 2023). Earthquake damage reduction, reduced repair and rehabilitation expenses, increased serviceability under repeated wind loads, reduction of non-structural damage, and increased functionality in the post-hazard period are all contributing factors to economic efficiency over the life-time of a building. In large commercial and residential high-rise buildings, these benefits are especially important as downtime, repairs and recovery can be costly (Babar & Patil, 2025). As a result, cutting-edge damping technologies are increasingly recognised as important investments in building resilience, sustainability and human safety. The literature also reveals a robust historical evolution in this field, with many state-of-the-art reviews on passive, semi-active, active and hybrid control systems and their theoretical development and real-world applications to buildings and bridges. This expanding body of knowledge provides a solid foundation for a review paper on response analyses and design of tall steel buildings with semi-active dampers. This review is technically significant as it integrates structural dynamics, smart control systems, optimal design, retrofits and economic analysis into a holistic approach for next-generation high-rise building design.

2. Literature review

Rouzbeh Doroudi et.al (2020) This research explores the control of seismic response of the structure using dampers through the application of advanced control and optimization strategies. Fuzzy logic controller is used to predict the control force and voltage for the Active Tuned Mass Damper (ATMD) and Magnetorheological (MR) damper, in which, tuning of membership function and development of an effective rule base play a key role in improving the performance. The Tuned Mass Damper (TMD) parameters are tuned to reduce the seismic responses. Moreover, the TMD parameters and fuzzy controller are fine-tuned using the observer–teacher learner-based optimization (OTLBO) technique. The findings reveal that the optimized models provide a significant reduction in peak seismic response, highlighting the improved stability of the structures, effectiveness in vibration control and overall performance under seismic loads (Lavasani & Doroudi, 2020). **Hyun-Su Kim et.al (2021)** High-rise buildings with innovative and complex forms, such as tilted, twisted and tapered buildings, require greater protection from excessive lateral deformation even under static loading conditions. The seismic response control of a 100-story tall tilted building is investigated in this study using a semi-active tuned mass damper (SATMD). The system comprises two 300 kN magnetorheological (MR) dampers at the top of the structure with a fuzzy inference system controller (FISC). The controller's parameters were fine-tuned using a multiobjective evolutionary algorithm for enhanced performance. The effectiveness of the system was verified by comparing it with a semi-active groundhook controller and an optimal passive tuned mass damper (TMD). The findings show that the proposed fuzzy-controlled SATMD has a better seismic response mitigation effect, enhancing the building's performance. The system also offers similar or better efficiency while using less than 30% of the mass of a passive TMD, confirming its efficiency and feasibility (Kim & Kang, 2021).

Adnan Kiral et.al (2024) This research examines the effectiveness of new advanced semi-active control systems, 2-4 direction and displacement-dependent (2-4DDD) and 2-4 displacement-velocity-dependent (2-4DVD) dampers, in the seismic response of multi-degree-of-freedom (MDOF) structures. The study uses a 3-story steel frame modeled in OpenSees and real earthquake data to assess the performance of various control strategies, including standard nonlinear viscous dampers (NVDs). A series of parametric studies is performed to identify the most effective design parameters, and novel design approaches for 2-4DDD and 2-4DVD control are developed. Significant improvement in performance is observed with the 2-4DVD control which decreases inter-story drift and base shear by up to 72% and 32% than the NVDs, respectively. It also reduces the damping force and acceleration by up to 60% and 87%, respectively, compared to 2-4DDD control. The 2-4DVD system offers a more stable and smooth response than 2-4DDD, which is unstable in response to high-frequency earthquake excitations (Kiral et al., 2024a).**Denise-Penelope N. Kontoni et.al (2021)** This paper analyses seismic behavior of plan-irregular T-shaped steel high-rise building (HRB) taking into account the vital role of soil-structure interaction (SSI). The structure, with and without SSI conditions and with fixed base, was modeled as 3D to evaluate the vibration reduction and displacement control of tuned mass damper (TMD) systems under four various earthquakes records. The study involved six plan arrangements of TMDs, with the placements mostly on the top level when using the fixed-base model, whereas the other TMDs were placed at two levels in between the height of the building in the SSI model. The findings show that TMDs are more effective in alleviating seismic responses in SSI conditions than when assuming fixed bases. Moreover, a multi-level TMD distribution is much more efficient, especially in the cases of two or four TMDs, which results in a better decrease in displacements, base shear, and structural response, and thus the provision of high seismic resilience (Kontoni & Farghaly, 2024).

Mohammad Ghorbanzadeh et .al (2022) This paper assesses the semiactive tuned mass dampers (STMDs) performance in mid-rise steel buildings with consideration of soil-pile-structure interaction (SPSI), which is usually not addressed in standard fixed-base analyses. The seismic performance of building construction on layered soil under different geotechnical conditions (shear strength and stiffness) was analyzed using three-dimensional finite element modeling in OpenSees. The findings show that the consideration of SPSI has a great impact on the structural response, resulting in a decrease in the efficiency of STMDs. In particular, the accelerations and displacements of the structure accelerate and these displacements are also apparent especially in top storey displacements when the SPSI is incorporated. Despite the fact that a decrease in base shear can be observed through mobilized passive resistance around the foundation of piles, the general control ability of STMDs reduces in real soil conditions. These conclusions demonstrate that fixed-base assumptions can lead to misleading and non-conservative designs, and it is important to consider SPSI effects in order to have the correct seismic performance analysis and a correct design of dampers (Ghorbanzadeh et al., 2022). **Liangkun Wang et.al (2024)** In this research, the authors examine how the uncertainties involved in the soil structure interaction (SSI) affect the seismic performance of the tuned mass dampers (TMDs) in high-rise buildings and the reasons why a semi-active tuned mass damper (STMD) should be considered to address the shortcomings of passive systems. The traditional passive TMDs are affected by frequency and damping detuning caused by uncertainties in structural and soil parameters, which result in poor efficiency. The proposed STMD can simultaneously tune frequency and damping ratio by changing mass and regulating the eddy current damping with real-time adjustment of air gap amplitude with an output-based algorithm. Firstly tested on a single-degree-of-freedom (SDOF) system, the results demonstrate that the performance is greatly reduced when damping is the only parameter considered, but joint frequency and damping control results in optimal performance. A 40-story benchmark structure under varying SSI conditions is another confirmation that STMD is an effective method of reducing structural displacements as compared to passive TMDs. Also, passive TMD performance degrades at detunings of ±15% stiffness, whereas STMD is more robust and stable with tuning (Wang et al., 2024b).

Amir Masoumi Verki et.al (2022) The significance of seismicity in developing countries and building fortification is a subject of great concern. Thus, the analysis of some solutions including the creation of new technologies is highly significant to examine the damage on retrofitted structures with the help of probabilistic methods. Federal Emergency Management Agency takes into account three levels of performance by taking into account various scenarios, intensity and duration. The sampling and reduction of ground movements largely determine the focus of the research. The most widespread are intensity-based tests, which calculate the response of buildings to a given seismic intensity. Scenario-based assessments are used to estimate how the buildings would respond to various earthquake scenarios. One of the most effective is considered to be a risk-based assessment. This study is a pragmatic approach to developing nations where there are numerous active faults, high-rise constructions and ineffective implementable strategies. Thus, two high-rise steel buildings have been modeled and evaluated in order to fulfill the primary objective. The role of buckling-restrained braces in the elastic design of both buildings is firstly confirmed. The buildings had repairable damage at the central top and certain life safety hinges at the bottom in the nonlinear static range (Verki & Preciado, 2022). **Huidong Zhang et.al (2021)** This paper presents a pneumatic spring-oil damper of adjustable stiffness to address the shortcomings of traditional velocity-dependent dampering oil dampers which can fail during earthquakes because of large stroke and residual motion. The force-deformation characteristics and hysteretic action of the proposed damper are calculated and analyzed analytically. Its capability is justified by dynamic testing of 10 and 20 stories of three-dimensional steel frame buildings with five typical ground motions. Findings indicate great enhancements compared to conventional dampers, and peak displacement decreases of about 10-75, inter-story drift decreases of 25-60, and inter-story shear force decreases of 20-60. The analysis of energy shows that the new damper absorbs approximately 30-70 per cent of the total seismic input energy, which proves the high efficiency of the damper. Also, the parametric analysis reveals that the axial length, inner diameter and starting pressure have a strong impact on performance. Altogether, the proposed damper is a safer, more stable and efficient solution to seismic energy dissipation in structures (H. Zhang & Liu, 2021).

Zhenfeng Lai et.al (2024) The proposed research designates the velocity-squared damping hybrid mass damper (VSD-HMD) that improves the vibration control effectiveness in high-rise buildings during different load conditions. Another issue with traditional hybrid hybrid mass dampers (HMDs), which are tuned mass dampers with active mass dampers (AMDs), include large stroke and control force, particularly with poor wind loads and space restrictions. To escape these drawbacks, the suggested system combines a velocity-squared damping device (VSDD) and an AMD. The Canton Tower is modeled numerically, and the best force and the velocity relationships are achieved. The critical wind-load conditions are considered in three cases of the system performance based on linear quadratic Gaussian control strategy and also confirmed by real-time hybrid simulation (RTHS). Findings show that VSD-HMD significantly decreases the AMD control force and stroke and VSDD stroke in comparison to the traditional HMD systems. The fact that the simulation and experimental results are close to each other is a confirmation of the reliability, efficiency, and practical applicability of the proposed vibration control system (Lai et al., 2024). **Sadegh Etedali et.al (2023)** The paper examines the probabilistic seismic performance of high-rise buildings fitted with a friction tuned mass damper (FTMD) taking into account soil-structure interaction (SSI) and structural, soil, foundation, and near-fault ground motion model uncertainties. A 40-story building is considered as a benchmark under different conditions such as three types of soils, three earthquake magnitudes, three distances of the fault, and three levels of seismic performance and there are 162 reliability analyses. Findings reveal that FTMD can be effective in minimizing seismic responses with an average of 51.13, 49.42, and 17.50% maximum inter-story drift ratios being reduced by the FTMD over uncontrolled structures. Nevertheless, the device is not completely compliant with the seismic code at the immediate occupancy level, especially during high magnitude earthquakes and near fault conditions. It works better on the levels of life safety and collapse prevention by minimizing chances of failure in the majority of cases. Moreover, the growing softness of the soil also harms the FTMD efficiency, which underscores the need to consider uncertainties to conduct a sound assessment of seismic reliability (Etedali et al., 2023a).

Sr. No.	Author & Year	Methodology	Results (Quantitative)	Findings & Outcomes
1	Doroudi et al. (2020)(Shangapour et al., 2025)	Fuzzy logic controller + OTLBO optimization for ATMD & MR dampers	Peak seismic response significantly reduced	Optimization enhances vibration control and structural stability
2	Kim et al. (2021)	Semi-active TMD (SATMD) with MR dampers + FISC optimization	Comparable performance with <30% mass of passive TMD	Efficient and practical semi-active control system
3	Kiral et al. (2024)(Kiral et al., 2024b)	2–4DDD & 2–4DVD semi-active dampers (OpenSees MDOF model)	Drift ↓72%, Base shear ↓32%, Acceleration ↓87%	2–4DVD provides superior and stable seismic control
4	Kontoni et al. (2023)(Kontoni & Farghaly, 2023)	TMD in irregular high-rise steel building with SSI	Significant reduction in displacement & base shear	Multi-level TMD improves seismic performance under SSI
5	Ghorbanzadeh et al. (2022)	STMD with soil–pile–structure interaction (SPSI)	Increase in displacement & acceleration; reduced damper efficiency	SSI must be considered for accurate and safe design
6	Verki et al. (2022)	Probabilistic seismic assessment with BRB retrofitting	Repairable damage + life safety hinges observed	BRBs enhance seismic resistance in high-rise steel buildings
7	Zhang et al. (2021)	Variable stiffness pneumatic oil damper	Displacement ↓10–75%, Drift ↓25–60%, Shear ↓20–60%, Energy dissipation 30–70%	Highly efficient damper with improved safety and stability
8	Lai et al. (2024)	VSD-HMD hybrid system + LQG control	Reduction in control force, AMD stroke, and VSDD stroke	Efficient hybrid system for wind vibration mitigation
9	Etedali et al. (2023)	Probabilistic FTMD with SSI	Drift reduction ≈51.13%, 49.42%, 17.50%	Effective for life safety; limited at extreme seismic levels

3. Paper contributions

The paper will make a positive contribution to the development of the practice in structural engineering by demonstrating a thorough and technically unified overview of the damping technologies in high-rise steel structures in particular semi-active control systems. To begin with, the research gives a current and comprehensive literature review of the passive, semi-active, active, and hybrid mass damper systems, including the principles of their work, design factors, and their efficiency in reducing the vibrations caused by wind and earthquakes in tall steel buildings. Secondly, it methodically summarizes and evaluates real-life experience of mass damper systems in building-like constructions in various regions, which allows comprehending the current trends in practical implementation in a clear way. The paper also assesses the state of art control algorithms applied to semi-active systems and to hybrid systems to determine their effectiveness in vibration control in real time and adaptive performance (Farahpour & Hejazi, 2023). It also critically looks at the shortcomings of the current control systems such as tuning problems, power needs, stroke capacity, and complexity of implementation. The other contribution is the identification of the gaps between theoretical research and engineering practical applications particularly in the case of high-rise steel buildings. Lastly the paper evaluates the development of installation trends and gives an idea on the future research directions with strong focus on intelligent and adaptive damping systems, which is increasingly important in improving structural safety, serviceability and long-term performance.

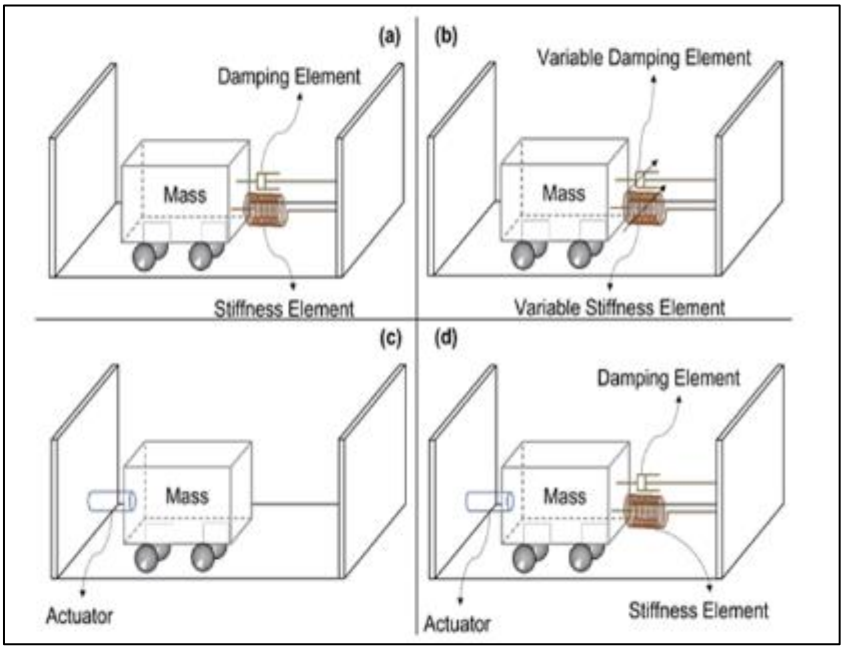

Figure 1 Classification of Mass Damper Systems in Buildings

The figure shows vibration control systems of high-rise buildings that have four varieties of mass damper systems. Passive tuned Mass Damper (PTMD): (a) A fixed mass is attached by means of stiffness and damping components, often with a reduction of structural response by 20 -40% when tuned. Semi-Active Tuned Mass Damper (SATMD) is used in (b) with variable stiffness and damping to achieve adaptive control, and higher efficiency (3060) percent. In (c) Active Mass Damper (AMD) an actuator is used to impose external force, which has high control performance (5070% reduction) but which consumes a lot of energy. In (d) Hybrid Mass Damper (HMD), passive and active parts are factored in, which offers equal performance (4065% efficiency) and energy requirements are moderate (Wang et al., 2022).

4. Paper structure

The paper is structured to analyze and design high-rise steel buildings with semi-active dampers in such a way that it allows a smooth flow between the literature review and the conclusions (He et al., 2023). Section 4 provides an overview of the past studies, including the history of development and use of passive, semi-active, active, and hybrid mass damper devices in high-rise buildings. This part brings the developments of both theory and experiments, which would give a fundamental knowledge of the benefits and working mechanisms of both damping strategies. Section 5 discusses constraints found in these studies, dividing them into hardware- or software-related issues, such as problems of practical implementation, constraints of sensing and actuating, computational needs and reliability. Section 6 describes the systematic literature review procedure used in the paper, its importance in detecting research gaps, synthesizing knowledge, and making sure that the results are founded on a strong, systematic inquiry. In section 7, the findings of the literature search are provided with an emphasis laid on the real-life applications of mass damper systems and the effectiveness of the various control algorithms and the performance results of the mass damper systems in different structural conditions. Lastly, Section 8 wraps up the study, summarizing the main findings and giving recommendations on how the research can be used to initiate further studies, especially in streamlining the semi-active damping systems in high-rise steel buildings.

4.1. Semi-Active Mass Dampers

Semi-active mass dampers (SATMDs) have proven to be a very efficient and adaptive tool in reducing vibration in high-rise buildings that combines the benefits of passive and active control with minimal external energy requirements. Traditionally, the SATMD performance was first studied by Hrovat et al. (1983) who showed that semi-active devices could obtain similar energy dissipation to fully active systems and higher performance as compared to conventional passive tuned mass dampers (PTMDs) even without the high power requirements of active devices (Spencer and Nagarajaiswamy, 2003; Yalla et al., 200 ABÉ (1996) also contributed to the development of SATMD by developing a feedback-based control scheme based on a single-degree-of-freedom model that also demonstrates better performance in impulse loading and seismic loading than traditional PTMDs. Later researchers, Ricciardelli et al. (2000), brought in empirical optimization algorithms, allowing the SATMD properties to dynamically adapt as measured structural response, not requiring full knowledge of the main structural system, or even the form of excitation introduced. Setareh (2002) came up with a ground-hook tuned mass damper (GHTMD) to counteract human induced floor vibrations with about 14% higher performance than classical PTMDs and robust performance under off-tuning conditions (Shih & Sung, 2021). Xu et al. (2003) have investigated MR damper-based SATMDs using neural network algorithms, which consider the time delay effects in the real-time control of multi-degree-of-freedom reinforced concrete models under seismic load. Nagarajaiah et al. (2004) and Nagarajaiah and Varadarajan (2005) explored variable stiffness SATMDs that could real-time re-tune their frequency, and found that semi-active schemes could re-implement full-active systems at a much lower power cost. Yan et al. (2007) proposed model predictive control (MPC) in MR-damper SATMDs, minimizing nonlinear earthquake behavior of twenty stories benchmark buildings. Lee et al. (2010) experimental studies verified that the Lyapunov-based and cost-function neuro-control algorithms have better results than passive systems in minimizing acceleration and displacement in full scale steel frame structures (Fu et al., 2019). Kang et al. (2011) showed that ground-hook MR-controlled SATMDs offered comparable control compared to active systems with reduced energy usage, whereas Laflamme et al. (2011) created adaptive neurocontrollers that operated well during seismic and wind excitation. These early works formed the basis of the current generation of semi-active damping systems, which combine intelligence, flexibility and energy conservation to tall steel buildings.

More recent studies have further enhanced the SATMD applications by applying more sophisticated control techniques, real time tuning, and variable mass configurations to overcome the detuning and stochastic excitation issues. The impulsive semi-active mass damper (ISAMD) was proposed by Shih and Sung (2021) with a directional active joint to avoid detuning, and its maximum and RMS displacement attenuations were better than those of PTMDs under seismic loads. Dai et al. (2021) explored SATMDs on MR dampers to control vortex-induced vibrations (VIV) in long-span bridges and proposed real-time tuning and mass stroke limitation techniques to improve resilience to frequency uncertainty. In Wang et al. (2021), semi-active mass dampers were applied to a human-induced vibration subjected to footbridges, with a wavelet-transform-based controller to adjust the mass of the damper in real-time based on the instantaneous identification of the frequency (S. Zhang et al., 2025). The findings showed a high vibration control performance on single-pedestrian, crowd-induced, and stochastic excitations, which was superior to conventional PTMDs. The research also showed the importance of human-structure interaction whereby the loading of pedestrians may enhance or diminish structural responses based on the input frequencies. These recent investigations demonstrate that SATMDs not only offer the best vibration control to seismic and wind loads but also show flexibility to stochastic and dynamic excitation conditions, thus being especially good in high-rise steel buildings where serviceability, occupant comfort, and structural integrity are paramount.

4.2. Active/Hybrid Control

Active and hybrid control systems have become a key development in the reduction of vibrations in high rises made of steel, specifically in areas prone to seismic and heavy wind risks. Active systems, as opposed to passive ones, use actuators and sensors to provide forces directly to the structure, allowing it to adapt to a changing dynamic load on a real-time basis. Chen et al. (2021) explored the concept of active mass damper (AMD) systems based on stroke-limited actuators and proposed a variable-gain state-feedback controller that could control mass strokes and simultaneously attain effective response dissipation (Tai & Ikenaga, 2022). Their analysis of a high-rise building and a four-storey experimental structure proved the effectiveness of active control to minimize the peak accelerations and keep actuator feasible. In the same vein, Ramírez-Neria et al. (2021) have come up with a generalized proportional-integral observer-based active disturbance rejection control (ADRC) of seismically excited buildings. Their experimental work on a five storey structure established great vibration dissipation and strength against unknown external disturbances proving the practicability of the advanced observer-based active controllers in the real world.

Concha et al. (2021) proposed an automatic tuning algorithm of a sliding mode controller to active tuned mass dampers (ATMDs), with the aim to provide sufficiently quick transient response and active control of forces during seismic excitation. Zhu et al. (2021) suggested a hybrid vibration damping strategy of footbridges that integrated passive tuned mass dampers with crowd-flow control theories to overcome the issue of detuning and inability to adapt to changing conditions of traditional passive dampers (Patil & Patil, 2024). Their approach effectively reduced the maximum acceleration and was not exceeding the serviceability criteria, which emphasized the multi-purpose of the hybrid method in dynamic human-structure interactions. Koutsoloukas et al. (2022a) concentrated on robust model predictive control (RMPC) of ATMDs in real high-rise towers, and assessed the algorithm under parametric uncertainties in stiffness, damping, and actuator performance. RMPC system performed better than the H and controllers as well as passive tuned dampers (PTMD) in terms of vibration reduction and energy consumption. The study of Zhou et al. (2022), when applying an LQR with variable-gain algorithm to control a 600 m tall tower during Super Typhoon Hato, showed the efficiency of the system in the real-life extreme wind conditions. The new reinforcement learning applications have enhanced the hybrid control approaches even more. Koutsoloukas et al. (2022b) applied a deep deterministic policy gradient (DDPG) algorithm to ATMD vibration control, and both nominal and -10% uncertainty in stiffness/damping were experimented with. The DDPG performed similarly to LQR controllers and much higher than PTMD, suggesting machine learning-based adaptive controllers have the potential to provide robust and optimal high-rise vibration mitigation. All these studies demonstrate that hybrid systems, comprising of active control with passive or semi-active components may lead to energy-efficient, flexible, and extremely robust performance (Hamza et al., 2024). They maximize actuator demand, minimize power consumption and provide occupant comfort whilst managing multi-modal vibrations well in seismic and wind induced excitations.

5. Systematic evaluation of literature with control system application

The modern urban architecture has depended on high-rise steel buildings because of their strength, flexibility and speediness of construction. These structures however become more prone to the lateral vibrations caused by the wind, earthquakes and operational forces when they continue to get higher and thinner. These dynamic actions may jeopardize serviceability, habitation and structural soundness (S. Zhang et al., 2023). The engineers have resorted to structural control systems, especially semi-active damping devices to alleviate these problems, which can dynamically control the response of a building to different conditions. Semi-active dampers have the benefit of being able to tune the damping behavior or stiffness in real time with very little external power input as compared to fully active systems and offer a more efficient performance than passive devices. Recent studies have addressed the application of fluid viscous dampers, buckling restrained braces, tuned mass dampers, and hybrid control system in new works and in retrofit (Dominguez et al., 2023). It has been shown that the introduction of these damping solutions in high-rise steel buildings can greatly decrease inter-storey drift, acceleration of the floor, and lateral movement, thus improving the safety and comfort of the structure and the occupants. Moreover, life-cycle cost analysis shows that installation costs of such devices can increase, but over the long run, maintenance and repair savings, as well as enhanced resilience, make semi-active damping systems a cost-effective approach to high-rise construction.

A logical literature review is essential in learning the performance and optimization of semi-active dampers in high-rise buildings with steel structures. In contrast to traditional literature reviews that might be based on experience or selective literature, systematic literature reviews use a systematic search process with well-developed objectives, inclusion and exclusion criteria as well as recorded methods (Kitchenham and Charters, 2007). This method minimises bias, and provides full coverage of pertinent research, and enables statistical or meta-analytic test to determine patterns and trends (Parvaresh & Mohebbi, 2022). Systematic reviews have been used in civil and structural engineering in topics like building information modeling (Panah & Kioumarsi, 2021), sustainable structural engineering (K & Gautam, 2021), machine learning applications in structural health monitoring (Flah et al., 2021), infrastructure megaproject management (Babaei et al., 2021), and artificial intelligence in sustainable development (Manzo These systematic methods offer evidence based understanding of the location, formulation and maximization of damping apparatuses in practical building structures, so engineers can make wise judgments on their incorporation. The systematic assessment will enable the identification of gaps in knowledge, confirming the results of the experiments, and creating the practical principles of semi-active damper installation (Pawar & Salgar, 2025). Therefore, a combination of high-rise steel building constructions and evidence based on systematic literature reviews will guarantee that structural control systems are applied in a manner that gives maximum performance, safety, and economic effectiveness besides offering a concise research base upon which future developments in adaptive building technologies can be enhanced.

5.1. Systematic Evaluation Objective

Systematic review of high-rise steel buildings equipped with semi-active dampers is aimed at reviewing and synthesizing the literature that specifically deals with the actual use of mass damper systems in building-like structures (Arabzai et al., 2026). As opposed to experimental systems, bridges, or wind turbines, this assessment focuses on those studies in which the damping technology has already been used in real building conditions, making sure that it is practically relevant. Passive, semi-active, active, and hybrid mass dampers are considered, and other types of control systems, like tuned liquid dampers, are avoided to ensure a consistent focus on the solutions using mass dampers. An important aspect of the analysis includes the knowledge of the algorithms and control measures utilized in these real-life applications, such as the adaptive, feedback-based and optimization methods that control the semi-active response of the dampers. The performance metrics that can be compared with the help of this approach include the reduction of vibration, displacement control, structural integrity, and occupant comfort. In the review, the practical considerations include the installation, effectiveness under wind and seismic loads, and the integration of the control systems into the structural framework, by focusing on mass-damper implementations in buildings. The result offers designers and engineers an insight into the potential of technology as well as operational constraints of semi-active mass dampers to inform optimised design and application in contemporary high-rise steel buildings.

5.2. Search strategy

In modern structural engineering, much attention has been paid to the study and design of high-rise steel structures with semi-active dampers as there is an increasing trend towards the desire to possess sound and serviceable tall structures in seismic and wind-prone areas. It is convenient that the semi-active damping systems offer a tradeoff between performance efficiency and energy usage, offering superior vibration reduction, displacement regulation and structural integrity over the conventional passive damping devices since systems that are capable of modifying their characteristics dynamically. To evaluate the recent progress in this area according to the search strategy developed by Reymert et al. (2022), a systematized literature review was conducted (Kurlapkar et al., 2023). The review applied systematic database search in the form of Boolean operators AND/OR to combine relevant phrases and narrowed down a couple of times to be inclusive and precise. To start with, broad search words were used to find out the number of studies in Scopus and narrow phrase searches were conducted later on to obtain specific findings. The approach was to create a list of semi-active mass damper applications and control algorithms as comprehensive as possible and expand the scope of the research by prior researchers. This kind of approach made it possible to set up key tendencies, design strategies, optimization strategies and practical implementation of semi-active dampers that would provide a sound ground to the examination and design of high-rise steel structures, being optimized in regards to dynamic behaviour and structural stability over the long run.

5.3. Screening process

A systematic screening process was carried out in order to obtain the most relevant literature to analyse and design high-rise steel buildings with semi-active dampers. To determine the accuracy and relevance of the search results, firstly, the ones that were not written in English, did not correspond to the goals of the study, or were duplicated were filtered out. A total of 424 unique studies were identified with the use of a phrase-based Table 1 search approach. Also, 37 other studies were added on the basis of references mentioned in these results which made the final dataset of 461 documents. These included 70.5% journal articles, 26% conference papers, and 3.5% books, book chapters, or technical reports. (Wu et al., 2022) Temporal analysis of these studies suggests that there has been a rise in interest in structural control technologies, especially mass damper systems with a significant increase in publications after 2009. Most studies are based in five countries; China, Japan, the United States, Taiwan and Iran, which also provided 61.5 percent of the collected literature. The provided screening process gave an in-depth and high-quality base to examine the current situation with semi-active damping systems of high-rise steel structures and assess the technological tendencies, design approaches, and contributions to research worldwide in detail.

6. Fluid viscous damper

Due to their tallness and slenderness, high-rise steel structures are highly vulnerable to dynamic forces like wind gusts, earthquakes and other vibrations of machines or human actions. Significant structural responses can be caused by these dynamic excitations such as over-inter-storey drift, floor accelerations and even progressive damage unless mitigated properly. In this regard, the fluid viscous dampers (FVDs) have become one of the most efficient passive control devices to control vibrations in tall buildings. FVDs work on the principle that the kinetic energy in structural motion is converted to heat energy which is removed by allowing a highly viscous fluid (usually silicone oil) to flow in a closed cylinder. The mechanism of this energy dissipation does not depend on the structural stiffness so that FVDs can be very useful when used as new constructions and retrofitting projects. FVDs have stable performance over a wide range of frequencies and amplitudes as compared to traditional damping solutions which only work well in narrow frequency bands, which is especially important in high-rise steel buildings which are susceptible to irregular seismic and wind excitations. Their flexibility, strength and predictable reaction makes them a vital element of modern tall-building design that helps in the creation of a resilient structure, comfortable living conditions, and ease of service.

Recent studies have centred not only on the basic performance attributes of the fluid viscous dampers, but also on their optimum incorporation in the high-rise buildings. The performance of FVDs relies greatly on the location of FVDs in the building, which is usually where the modal deformation is the greatest, i.e. along the main lateral load-resisting frames or at the top stories where inter storey drifts are the greatest. Research has been conducted into a range of methods to estimate the best number, height and orientation of dampers in order to achieve the greatest dissipation of energy and minimize structural behavior during seismic loads. Developments in FVD technology have improved their efficiency, durability and cost-effectiveness and increased their practical applications. Analytical, numerical, and experimental studies show that with well-placed FVDs in buildings, the peak acceleration, lateral displacement, and structural demand can be considerably reduced. FVDs are also favored due to their comparatively simple installation, and minimal maintenance needs, which means that they are more popular when it comes to new high-rise construction as well as retrofitting of existing steel structures. Altogether, fluid viscous dampers are a necessary instrument in improving the stability of structures, reducing the detrimental impact of earthquakes, and maintaining the safety and effectiveness of high-rise steel structures in the long term.

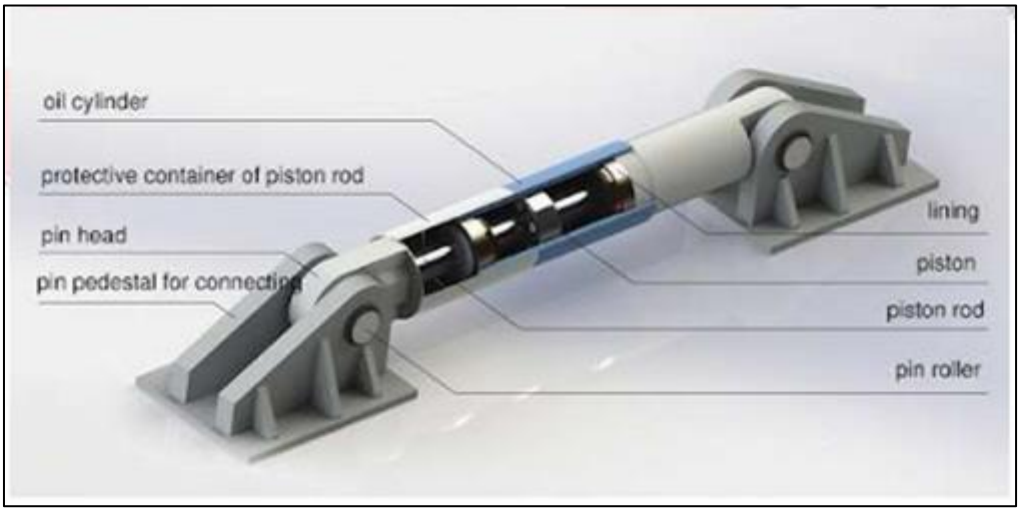

Figure 2 Fluid Viscous Damper Structure

7. Tuned mass dampers

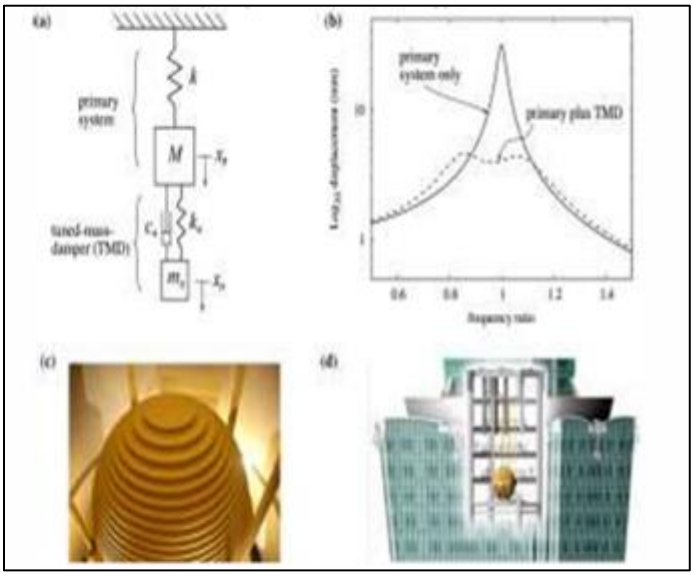

Figure 3 Tuned Mass Dampers

The high-rise steel buildings, due to their height, slenderness, and flexibility, are very vulnerable to dynamic excitations that include wind forces, seismic loads, and vibrations caused by people. In order to alleviate these effects and enhance structural integrity as well as occupant comfort, engineers have increasingly turned to sophisticated vibration control systems. Tuned Mass Dampers (TMDs) are among the most commonly used solutions and they operate in a way that they add an auxiliary mass to the primary structure using springs and damping elements. The key concept of TMDs is frequency tuning: the natural frequency of the secondary mass system is set to correspond to the predominant vibration mode of the building. When the building is perturbed by the outside stimuli, the TMD vibrates in anti-phase with the building and absorbs and dissipates the energy that would otherwise increase vibrations. The mechanism works especially well with tall and slender buildings under wind-induced vibrations, which results in less lateral movement, inter-storey movement, and acceleration intensity. TMDs have been shown to offer benefits to structural integrity and to occupant comfort, but their response can be poor in the presence of multi-directional seismic loads, due to their tuning being normally optimized to a single dominant mode. Nevertheless, TMDs continue to play an important role in the dynamic control of high-rise structures, providing a passive, highly dependable, and easily maintainable method of reducing the effect of the wind on the structure.

Besides TMDs, semi-active damping system like fluid viscous dampers (FVDs) provide a more flexible and adaptive solution to seismic response control in high-rise steel structures. FVDs minimize vibrational energy by a velocity-dependent resistance mechanism, which offers continuous damping over a broad frequency range. FVDs can also accommodate changes in structural properties, changing seismic input, and multi-directional excitations, unlike passive TMDs which are optimized to specific modes and are especially useful in areas susceptible to earthquakes. Contemporary studies not only highlight the use of damping devices but also their location and dispersion in the building height in order to optimize the energy dissipation. The location of the damper is optimized to make sure that important modes of vibration are effectively contained so that structural damage is minimized, residual deformations are minimized, and overall resilience is improved. The use of FVDs in combination with the current structural design frameworks allows engineers to develop performance based solutions, which are safe, functional and cost effective. The concurrent analysis of TMDs and FVDs demonstrates an expanded rule in the design of tall buildings: the efficiency of a vibration control system is not solely in the properties of the device, but also in the conscientious approach in location, tuning, and adaptation to the dynamic nature of the building. By this means, high-rise steel structures can attain a higher seismic performance besides enhancing comfort and reliability of operation under wind and earthquake loading conditions.

8. Discussion

The studies reviewed provide a clear indication that the combination of semi-active and advanced damping systems has contributed greatly in enhancing the dynamic performance of high-rise steel buildings when subjected to seismic and wind-induced loads. Based on the research findings of various studies, it is clear that semi-active tuned mass dampers (SATMDs), magnetorheological dampers as well as hybrid control systems are far more adaptable than traditional passive devices. Indicatively, optimization-based solutions like fuzzy logic controllers and evolutionary algorithms have demonstrated significant seismic response peak and inter-storey drift reduction, which underscores the significance of smart control plans in the contemporary structural design. Moreover, research, which takes into account the soil-structure interaction (SSI), notes that when realistic boundary conditions are not taken into account, much higher efficiencies of dampers might be estimated and thus, the need to integrate geotechnical influences in design analysis is underlined. The relative analysis of systems like TMD, STMD, and hybrid dampers shows that semi-active dampers are always effective compared to passive counterparts, especially in ensuring that the performance of the systems is maintained in conditions of detuning and different excitation nature. Along with the performance increase, the discussion shows that the performance of damping systems is extremely sensitive to the position of dampers, control schemes, structural design and loading conditions. State-of-the-art techniques, such as metaheuristic optimization, and real-time adaptive control, have also made engineers find the best damper placement and settings, leading to great displacement, acceleration and base shear reduction. Furthermore, hybrid systems with passive and active components have proved to be more robust and less energy consuming especially in high rise buildings where there are multi-hazard conditions. Another significant point of the findings is the increased significance of performance-based design and cost-life analysis of the damping systems, where the damping systems are considered not only in terms of reducing the response in the short term but also in the long-term economic and resilience. All in all, the literature suggests that the shift to intelligent, adaptive, and optimised structural control systems has been clearly established in which semi-active dampers are highlighted as a crucial technology in providing safety, serviceability and sustainability in future high-rise steel buildings.

9. Conclusion

Literature review of the analysis and design of high rise steel building with semi-active dampers clearly indicates that hi-tech damping technologies play a major role in improving structural performance when subjected to dynamic load. Research like Rouzbeh Doroudi et al. (2020) and Hyun-Su Kim et al. (2021) establish that with optimized semi-active systems, peak seismic responses can be reduced, and similar performance with less than 30% mass can be achieved when compared to passive systems. Adnan Kiral et al. (2024) found that advanced control strategies showed significant improvements in terms of the reduction of the drift to 72% and the reduction of base shear to 32% and acceleration to 87%. On the same note, Huidong Zhang et al. (2021) demonstrated the 10 to 75 percent displacement reductions and 30 to 70 percent energy dissipation of innovative damping devices. Nevertheless, research by Ghorbanzadeh et al. (2022) has shown that soil-structure interaction may decrease the efficiency of damper, which highlights the importance of realistic modelling. Liangkun Wang et al. (2024) showed that semi-active systems can be employed to damp the system stronger than passive dampers, even in the conditions of ±15% detuning. On the whole, the results prove that the semi-active dampers offer a better vibration control, better structural safety, and longer performance, which makes them an effective and efficient solution in the modern high-rise buildings of steel.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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