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Seismic Energy Dissipation Using Tuned Mass Dampers in Medium-Rise Buildings

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***Abstract*—Earthquakes can cause severe vibrations and structural damage in reinforced concrete buildings. This paper studies seismic energy dissipation using Tuned Mass Dampers (TMDs) in medium-rise buildings. A TMD is a passive control device consisting of a mass, a spring or isolator, and a damping system, and it is tuned to the fundamental frequency of the building to reduce unwanted vibrations. The study focuses on rooftop TMDs as a less invasive method of seismic retrofitting. A six-storey reinforced concrete residential building is considered as a case study, and its seismic response is evaluated with and without TMDs. Two TMD configurations using different isolators and damping systems are compared. The results show a reduction in roof acceleration and structural response after installing the TMD, and the configuration using rubber isolators with viscous dampers gives the greater reduction in roof acceleration. TMDs therefore offer a practical approach for improving the seismic performance of medium-rise buildings with minimal structural modification.**

***Keywords*—Tuned mass damper, seismic energy dissipation, medium-rise buildings, rooftop retrofit, passive vibration control, lead-rubber isolator, viscous damper, roof acceleration.**

I. Introduction

Earthquakes are among the most destructive natural hazards and can produce severe vibrations and damage to buildings. When an earthquake occurs, ground motion transfers energy into the building through its foundation, causing the structure to vibrate. Reinforced concrete buildings, which are widely used in urban areas, may experience significant structural response if adequate seismic protection is not provided.

Seismic control systems are therefore used to reduce the effects of earthquake-induced vibrations. One such passive control technique is the Tuned Mass Damper (TMD). A TMD consists mainly of a mass, a spring or isolator component, and a damping mechanism. It is designed and tuned according to the dynamic characteristics of the building. When the building vibrates during an earthquake, the TMD moves out of phase with the building motion and helps absorb and dissipate part of the seismic energy.

This paper focuses on the application of rooftop TMDs to medium-rise buildings. Such buildings are commonly found in urban areas and may require seismic retrofitting without major modifications to the existing structure.

The study examines the effectiveness of TMDs in reducing structural vibrations and roof acceleration using a six-storey reinforced concrete building as a case study. Different TMD configurations are considered, and their performance is compared to understand their potential for improving the seismic response of medium-rise buildings.

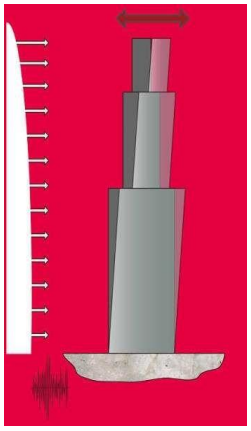


Fig. 1. Effect of earthquakes on buildings.

A. Purpose and Scope of the Study

The primary purpose of this study is to analyse the mechanics, integration and performance of Tuned Mass Dampers installed on medium-rise structures. The scope encompasses:

- Fundamental theory of seismic energy transfer and structural resonance.
- Theoretical formulation of mass–spring–damper systems.
- Structural and geometric characteristics of a sixstorey RC residential building in Tolmezzo, Italy.
- Integration methodologies for rooftop steel-bracedframe TMD systems.

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- Comparative evaluation of structural responses between the Original Building (OB), a Lead-Rubber Isolator TMD (TMD1) and a Rubber Isolator+ Viscous Damper TMD (TMD2).
- Practical implementation aspects, including cost, maintenance, real-world case studies and future smart technologies.

B. Importance of Seismic Energy Dissipation in Medium-Rise Buildings

A TMD is a vibration-control device used to reduce the movement of a building during dynamic loads such as earthquakes. It generally consists of a secondary mass, a spring and a damping mechanism, and it is designed so that its natural frequency is close to the dominant vibration frequency of the building.

When an earthquake occurs, the building starts to vibrate. The TMD moves relative to the building, producing a response that is out of phase with the building's motion. This transfers some of the vibration energy from the main structure to the TMD, where it is dissipated through damping. The principal benefits are listed below.

- *Reduction of seismic vibrations:* ground motion causes the building to vibrate from side to side. When properly tuned, the movement of the TMD's secondary mass counteracts part of this vibration and reduces the overall seismic response.
- *Reduction in lateral displacement:* excessive horizontal displacement can damage structural and non-structural components. A TMD absorbs part of the vibration energy and reduces the amount of sideways movement.
- *Reduction in inter-storey drift:* inter-storey drift is the relative horizontal displacement between two consecutive floors. Large drift can crack walls, partitions, windows and structural connections, and reducing the building's vibration helps limit it.
- *Protection of structural components:* strong vibrations produce dynamic forces and deformations in beams, columns, slabs, shear walls and connections. A properly designed TMD reduces the demand on these elements and helps limit damage.
- *Improvement of occupant comfort:* by reducing vibration and acceleration, a TMD contributes to a more stable feeling inside the building.
- *Control of resonance:* if earthquake excitation contains significant energy near the building's natural frequency, resonance can enlarge the response. A TMD tuned close to an important natural frequency counteracts this resonant response.

II. Tuned Mass Dampers (TMDS)

A Tuned Mass Damper (TMD) is a passive vibrationcontrol device used in buildings and other structures to reduce unwanted vibrations caused by earthquakes, wind, machinery or other dynamic loads.



Fig. 2. Tuned mass damper.

A. Main Components

A TMD generally consists of three main parts:

- *Mass:* an additional weight that moves relative to the building.
- *Spring:* provides a restoring force and controls the natural frequency of the TMD.
- *Damper:* resists the motion of the mass and dissipates vibration energy.

B. How Tuned Mass Dampers Work

A TMD is attached to a building to control its vibration, and it works through the relative movement of an additional mass.

- *Earthquake causes the building to vibrate:* ground motion produces dynamic forces that make the building sway.
- *TMD mass begins to move:* the TMD contains an auxiliary mass connected to the building through a spring and damper. As the building moves, the mass moves relative to it.
- *TMD is tuned to the building:* the stiffness and mass of the TMD are selected so that its natural frequency is close to the target vibration frequency of the building.
- *Relative motion reduces the building's response:* the movement of the TMD generates an opposing dynamic force, which reduces part of the building's vibration.
- *Damper dissipates energy:* the damper resists the relative movement and converts part of the vibration energy into heat.

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III. Why Focus On Medium-Rise Buildings?

Historically, the application of passive vibrationcontrol systems, specifically Tuned Mass Dampers, has been concentrated in tall skyscrapers and ultra-high-rise structures such as Taipei 101 and Citigroup Center. In high-rise structures, TMDs are primarily installed to control wind-induced sway and low-frequency lateral accelerations.

A. Prevalence in Urban Environments

Medium-rise structures, typically defined as buildings of 5 to 10 storeys (15 m to 30 m in height), constitute the majority of urban residential complexes, educational institutions, commercial centres and administrative facilities worldwide. Because of their sheer number, they represent the largest exposure of human life and financial capital during seismic events.

B. Limitations of Conventional Retrofitting

When retrofitting existing medium-rise RC structures to meet modern seismic codes, structural engineers face severe constraints:

- Base isolation: requires extensive foundation excavation, cutting of existing columns and significant land clearance around the building perimeter. This is often technically impossible in dense urban streetscapes and financially prohibitive.
- Concrete or steel jacketing: extends column and wall sections throughout all floor levels, reducing usable floor space, causing prolonged evacuation and disrupting tenants.
- Shear wall addition: demands massive continuous foundation upgrades and heavy interior construction.

C. The Rooftop TMD Alternative

Rooftop Tuned Mass Dampers offer a compelling solution for medium-rise buildings:

- *Minimal disruption of usable space:* construction is confined almost entirely to the roof level.
- *Non-invasive installation:* no foundation excavation or column modification is needed on the lower occupied floors.
- *Cost-efficiency:* structural modifications are localised to a top-level braced frame, significantly lowering labour and downtime costs.

IV. Seismic Energy And Dynamic Response

Seismic energy is the sudden release of stored strain energy along a fault, generating waves that cause a dynamic physical response in structures.

A. Energy Balance Equation in Structural Dynamics

When an earthquake strikes, seismic ground motion imparts a total energy E_I into the structural system. According to the principle of dynamic energy conservation, the total input energy at any instant t is balanced by various internal energy mechanisms:

$E_I(t) = E_K(t) + E_S(t) + E_D(t) + E_H(t)$ (1) where

- $E_I(t)$ is the total seismic input energy introduced through the foundation;
- $E_K(t)$ is the kinetic energy of the vibrating structural mass;
- $E_S(t)$ is the elastic strain energy stored temporarily in structural members;
- $E_D(t)$ is the inherent viscous damping energy dissipated naturally by non-structural elements and material friction;
- $E_H(t)$ is the hysteretic energy dissipated through permanent inelastic plastic deformation (cracking, rebar yielding).

B. Hysteresis and Structural Damage

In conventional uncontrolled structures, inherent damping (E_D) dissipates only a small fraction (typically 2 to 5%) of the seismic energy. Once the elastic strain thresholds (E_S) are exceeded, the remaining energy demand must be absorbed through hysteretic energy (E_H). Hysteretic dissipation is directly synonymous with structural damage: yielding of reinforcing bars, spalling of concrete and structural degradation.

When a Tuned Mass Damper is added, the modified energy balance becomes

$E_I(t) = E_K(t) + E_S(t) + E_D(t) + E_H(t) + E_{TMD}(t)$ (2) where $E_{TMD}(t)$ is the energy absorbed and dissipated by the auxiliary damper system. By maximising $E_{TMD}(t)$, the demand on $E_H(t)$ drops significantly, preserving the primary frame within its linear-elastic boundary.

C. Accelerogram and Seismic Input Dynamics

Seismic excitations are characterised by acceleration time-history profiles recorded during major ground motions. Peak Ground Acceleration (PGA) and velocity content dictate how energy transfers into the building, depending on the building's structural frequency.

V. Fundamentals Of Tuned Mass Dampers

A tuned mass damper is a secondary mass–spring– damper system mounted on a primary structure to reduce dynamic vibrations and sway caused by wind or earthquakes.

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A. System Components

A TMD is a secondary mass–spring–damper oscillator installed on a primary structural system. A complete structural TMD setup comprises three fundamental mechanical elements, described in Section II-A: the mass (m_d), the spring (stiffness k_d) and the damper (damping coefficient c_d).

B. Mathematical Governing Equations

Consider a primary structure modelled as a singledegree-of-freedom (SDOF) system equipped with a rooftop TMD, forming a two-degree-of-freedom (2DOF) coupled system. The coupled matrix equation of motion under the seismic ground acceleration $\ddot{x}_g(t)$ is

$$\begin{bmatrix} m_s & 0 \\ 0 & m_d \end{bmatrix} \begin{bmatrix} \ddot{x}_s \\ \ddot{x}_d \end{bmatrix} + \begin{bmatrix} c_s + c_d & -c_d \\ -c_d & c_d \end{bmatrix} \begin{bmatrix} \dot{x}_s \\ \dot{x}_d \end{bmatrix} + \begin{bmatrix} k_s + k_d & -k_d \\ -k_d & k_d \end{bmatrix} \begin{bmatrix} x_s \\ x_d \end{bmatrix} = -\begin{bmatrix} m_s \\ m_d \end{bmatrix} \ddot{x}_g(t) \quad (3)$$

where m_s, k_s and c_s are the mass, stiffness and structural damping coefficient of the main building frame; m_d, k_d and c_d are the mass, stiffness and damping coefficient of the TMD; and x_s and x_d are the displacements of the main building and the TMD relative to the ground.

VI. Frequency Tuning And Phase Shift

A. Resonance and Natural Frequency

Every structural frame possesses fundamental natural frequencies, given for the main structure by $\omega_s = \sqrt{(k_s / m_s)}$ (4)

When the frequency components of the seismic ground motion match the fundamental frequency of the building, the structure enters resonance. Resonance amplifies lateral deflections, storey drifts and structural stresses exponentially.

B. Tuning Mechanism and Optimum Parameters

To maximise energy transfer from the main structure to the secondary mass, the TMD's natural frequency $\omega_d = \sqrt{(k_d / m_d)}$ (5)

must be precisely calibrated ("tuned") relative to the structure's primary natural frequency. The mass ratio μ is defined as $\mu = m_d / m_s$ (6)

and typically ranges between 1% and 5% of the building's modal mass. Den Hartog's classic optimum tuning parameters give the optimum frequency ratio f_{opt} and optimum damping ratio ξ_{opt}, summarised in Table I.

TABLE 1: TUNING FORMULATION SUMMARY

Parameter	Symbol	Expression
Mass ratio	μ	$\mu = m_d / m_s$
Frequency tuning	f_{opt}	$f_{opt} = \omega_d / \omega_s = 1 / (1 + \mu)$
Damping ratio	ξ_{opt}	$\xi_{opt} = \sqrt{[\, 3\mu / (8(1 + \mu)^3) \,]}$

C. Phase Shift and Inertial Counteraction

When ground movement causes the building to sway laterally to the right, inertia acts on the tuned mass system. Because the TMD is tuned near the building's natural frequency, its motion shifts out of phase relative to the top floor (ideally approaching a 90° phase lag):

Building swaying right ⇒ TMD oscillates left ⇒ intercepts lateral shear force.

Building swaying left ⇒ TMD oscillates right ⇒ absorbs kinetic energy.

As the building sways right, the TMD pushes left, generating a counteracting inertial force at the roof level. This mechanical opposition limits top-level deflection and suppresses resonant build-up.

VII. Case Study: Design And Structural Details

To evaluate TMD effectiveness on medium-rise structures, a real six-storey RC residential building in Tolmezzo, Italy, was analysed.

A. Geometry and Footprint

The structure has a compact rectangular plan measuring 18.15 m in length by 11.90 m in width. The total height of 18.30 m is distributed uniformly across six storeys (a storey height of approximately 3.05 m). This geometry reflects standard urban proportions for mediumdensity housing across European and global regions.

B. Baseline Structural Deficiencies

In its original condition (OB, the Original Building), the primary frame was designed without modern energy dissipation systems. Under strong earthquake ground motion, dynamic stress concentrations emerge in the floor beam–column joints, producing elevated roof accelerations and high bending moment demand/capacity ratios ($M_{Ed}/M_{Rd} > 1.0$).

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VIII. Integration Of TMD Into The Building System

Tuned Mass Dampers are integrated into a building to reduce unwanted vibrations caused by wind, earthquakes, machinery or other dynamic loads. A TMD consists mainly of a mass, a spring and a damping mechanism, which is tuned to the dominant vibration frequency of the building.

A. Rooftop Braced Frame Architecture

To integrate the TMD without compromising floor space or imposing point loads on the roof slab, a specialised structural steel frame was introduced on the rooftop.

- *Steel frame support:* a braced structural steel frame is fixed directly to the building's primary RC column nodes at the roof level.
- *Load distribution:* this frame transfers the vertical weight of the mass slab directly into the main vertical columns, avoiding flexural punching shear in the roof slab.
- *Anchor system:* high-strength steel anchor bolts secure the frame to the beam–column joints.

B. Damping Configurations Studied

Two alternative rooftop TMD designs were implemented and evaluated (Table II).

TABLE 2: TMD DESIGN CONFIGURATIONS

CONFIGURATION	DAMPING AND ISOLATION MECHANICS
TMD1	High-damping lead-rubber isolators (LRB) supplying combined stiffness and damping.
TMD2	Standard rubber isolators providing stiffness, combined with a linear/nonlinear viscous damper.

IX. Results And Performance Evaluation

The structural performance of the case-study building under seismic loading was evaluated for three models:

- OB: the Original Building (un-retrofitted baseline).
- TMD1: retrofitted with the lead-rubber isolator TMD.
- TMD2: retrofitted with rubber isolators and viscous fluid dampers.

A. Accelerations and Shear Demands

The Original Building experienced severe top-floor acceleration spikes and elevated shear forces during the earthquake simulation. Incorporating TMD1 lowered the peak roof acceleration to 7.4 m/s². TMD2 achieved an even greater reduction, bringing the peak top-floor acceleration down to 6.3 m/s².

B. Bending Moment Demand/Capacity Ratios

Structural safety is assessed by the ratio of the applied design bending moment M_{Ed} to the resisting ultimate moment capacity M_{Rd}.

- When $M_{Ed}/M_{Rd} > 1.0$: structural capacity is exceeded, initiating yield hinges, structural cracking and permanent damage.
- When $M_{Ed}/M_{Rd} < 1.0$: the frame remains safely within its elastic operating boundary.

In the Original Building, numerous critical beam– column connections exhibited ratios well above 1.0. TMD1 reduced these stress concentrations significantly, bringing the ratios close to 1.0. TMD2 lowered M_{Ed}/M_{Rd} below 1.0 across all primary structural elements, preventing structural yielding during the design earthquake.

C. Energy Time-History Curves

Energy curves recorded during the time-history analyses show how the input energy E_I and hysteretic energy E_H change over time:

- *Without TMD:* hysteretic energy spikes rapidly following the peak ground-motion acceleration, indicating heavy inelastic structural cracking.
- *With TMD:* the cumulative hysteretic energy curve flattens substantially. The TMD absorbs and dissipates energy before it can deform the primary RC frame.

X. Advantages And Challenges Of TMD

A. Key Advantages

- *Passive operation:* operates without reliance on the external power grid during natural disasters.
- *Minimal impact on usable space:* confined to roof enclosures, avoiding interior disruption.
- *Targeted damping:* attenuates resonant sway mode shapes directly.

B. Design and Practical Challenges

- *Tuning sensitivity:* if structural stiffness degrades or live loads change significantly, the building's natural frequency ω_s shifts, and off-tuning can reduce TMD effectiveness.

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- *Space and stroke clearance:* the secondary mass requires unobstructed clearance on the roof to accommodate its stroke displacement without impacting the perimeter stops.
- *Added gravity load:* the rooftop framing must distribute the additional static mass of the TMD safely to the columns.

XI. Cost Considerations And Maintenance

A. Life-Cycle Economics

Compared with traditional seismic retrofits, rooftop TMDs offer distinct economic advantages:

- *No foundation excavation:* avoids expensive ground underpinning, pile installation and utility relocations.
- *Continued occupancy:* the building remains functional during installation, preserving tenant revenue.

B. Maintenance Schedule

To prevent degradation of spring elements or fluid leaks in viscous dampers, a periodic maintenance schedule is essential.

XII. Future Smart And Hybrid Tmd Technologies

- *Semi-active dampers (SA-TMD):* incorporate lowpower magnetorheological (MR) fluids that change viscosity in milliseconds under magnetic fields, continuously tuning the damping to match shifting frequencies.
- *Tuned mass damper inerters (TMDI):* use flywheel-driven inerter devices to multiply the effective inertial mass dynamically, allowing a smaller physical mass on the roof slab.
- *IoT and sensor integration:* real-time accelerometer networks stream operational data to cloud monitoring systems, alerting maintenance teams immediately to off-tuning or seal degradation.

XIII. Conclusion

Rooftop Tuned Mass Dampers provide an effective, non-invasive seismic mitigation strategy for medium-rise reinforced concrete structures.

By redirecting earthquake kinetic energy into an auxiliary mass system, TMDs preserve the main building frame within safe elastic limits.

The case study of the six-storey building in Tolmezzo demonstrates the practical performance of these systems:

- Un-retrofitted buildings exhibit unsafe flexural demand ratios ($M_{Ed}/M_{Rd} > 1.0$) under earthquake motions.
- Integrating a hybrid TMD with rubber isolators and viscous dampers (TMD2) lowers the peak roof acceleration to 6.3 m/s² and keeps M_{Ed}/M_{Rd} below 1.0.
- Confining the structural upgrade to a steel frame on the roof avoids tenant displacement, expensive foundation work and interior disruption.

While base isolation remains highly effective for new construction, rooftop TMDs represent a practical, costeffective solution for retrofitting the vast global stock of medium-rise buildings. Combining viscous fluid elements with emerging semi-active tuning technologies will further expand the performance and applicability of TMDs in urban seismic design.

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