The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2026

Volume 40, Pages 296-303

ICBAST 2026: International Conference on Basic Sciences and Technology

High Mass Ratio Tuned Mass Dampers Obtained Through Building Superelevations for Seismic Retrofit

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Abstract: Tuned Mass Dampers (TMDs) are widely adopted passive vibration control devices used to mitigate structural oscillations induced by wind and seismic actions. Conventional TMD systems typically involve relatively small auxiliary masses installed near the top of tall buildings. This paper investigates an alternative strategy for seismic retrofitting of existing structures based on large mass ratio TMDs obtained through building superelevations. In this approach, one or more additional storeys supported by seismic isolation devices behave as large tuned masses capable of reducing structural response during earthquake excitation. A comprehensive parametric numerical investigation is carried out in order to evaluate the influence of the mass ratio, structural period and damping characteristics on the effectiveness of the system. The results are summarized in a set of design charts that allow engineers to determine optimal tuning parameters. In particular, by using the obtained design abaci they can find a solution which minimizes both displacement and acceleration.

Keywords: Tuned mass damper, Retrofitting, Large mass ratio

Introduction

Tuned Mass Dampers (TMDs) represent one of the most widely used passive control systems for mitigating structural vibrations. The concept is based on the introduction of an auxiliary mass connected to the main structure through elastic and damping elements. When the system is properly tuned, the auxiliary mass oscillates out of phase with the primary structure, thereby dissipating a portion of the input energy (Alibabaei et al., 2023; Clarizia et al., 2024; De Angelis et al., 2012; Den Hartog, 1956; Giaralis et al., 2018; Gorini et al., 2019, 2022, 2024; Kaveh et al., 2020; Marrazzo et al., 2024; Salimi et al., 2021; Wang et al., 2020; Zucca et al., 2021)The effectiveness of this strategy has been widely demonstrated in tall buildings subjected to wind and seismic loads. A well-known example is the Taipei 101 skyscraper (Figure 1), which incorporates a 660-ton pendulum damper installed near the top of the building to control wind-induced vibrations.

Similar devices have been installed in several high-rise buildings around the world. In conventional applications, the auxiliary mass typically represents only a small percentage of the total structural mass, generally ranging between 1% and 5%. However, recent research has investigated the possibility of employing larger mass ratios in order to enhance vibration control efficiency.

One promising strategy for achieving high mass ratios consists of adding new storeys above existing buildings, supported by seismic isolation devices. In this configuration, the additional structural mass behaves dynamically as a tuned mass damper. This approach offers several advantages. First, it can significantly improve the seismic performance of existing structures designed according to outdated seismic standards. Second, the intervention can generate additional usable space, potentially offsetting retrofit costs. For these reasons, superelevation-based TMD systems represent an attractive solution for the seismic upgrading of existing buildings.

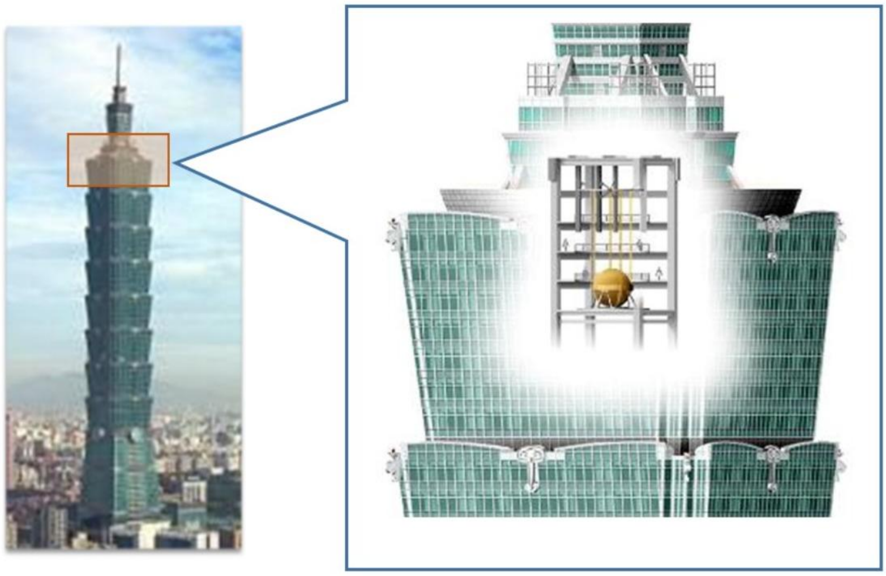

Figure 1. Tuned mass damper of 101 Tower– Taipei

The effective of this type of retrofitting has been already proved in wo cases: The Berry Street project in San Francisco (Figure 2) where two isolated stories have been added to an existing three storey building, and the retrofitting by means of a superelevaition of one floor made by steel structure by Marco Peroni in Faenza Italy (Figure 3).

Before the superelevation *After the superelevation*

Figure 2. Berry Street Building, San Francisco

Before the superelevation *After the superelevation*

Figure 3. Superelevation in Faenza by Marco Peroni

Methodology

The problem to be analyzed can be represented by the model in Figure 4

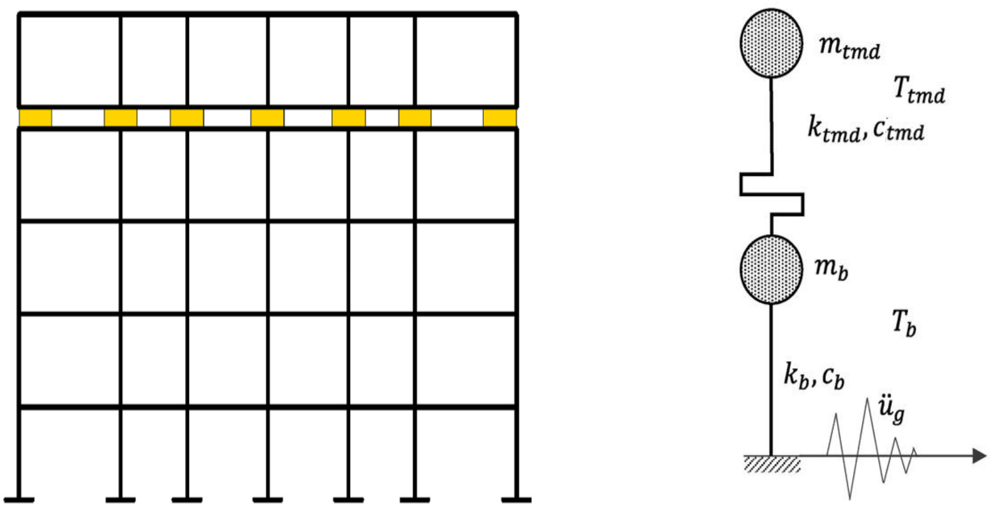

Figure 4. Modelling of the TMD

The dynamic behaviour of the mechanical model composed of two masses, namely the base mass m_b and the TMD mass m_{tmb}, characterized by natural frequencies $\omega_b = \sqrt{k_b/m_b}$ and $\omega_{tmb} = \sqrt{k_{tmd}/m_{tmd}}$ and damping ratios $\xi_b = \frac{c_b}{c_{b.crit}}$ and $\xi_{tmd} = \frac{c_{tmd}}{c_{tmd.crit}}$ has been investigated under several seismic ground motion records. The numerical simulations were carried out by varying the parameters associated with the system, namely the two natural frequencies, the relative mass ratio $\overline{m} = m_{tmb}/m_b$, and the damping ratio of the TMD ξ_{tmd}. The damping ratio of the main structure ξ_b was kept constant and equal to 0.05, which is commonly assumed for reinforced concrete (RC) structures. The purpose of the parametric study is to identify the combination of parameters that minimize the structural response of the building in terms of both absolute displacement and acceleration.

The parametric investigation was performed by varying the input parameters summarized in Table 1. In particular, the mass ratio $\overline{m}$, the TMD damping ratio ξ_{tmd}, the vibration period of the base structure T_b, and the vibration period of the TMD T_{tmd} were treated as variable quantities. A set of 100 artificial ground motion records was generated to approximately match (within ±10%) the Eurocode 8 design spectrum for soil type A, considering an intermediate peak ground acceleration (PGA) value of 0.15 g. Each record has a duration of 20 seconds and was generated using the well-known software SIMQKE.

Table 1. All the combinations are made for parametric analyses.

$\overline{m}$	0.10	0.20	0.30	0.40
ξ	0.15	0.20	0.25	0.3
T_b and T_{tmd}		0.00-4.00s	step 0.04s	

The obtained results were statistically processed by evaluating the upper bound fractile (95%) of the structural response obtained from the time-history analyses, considering both displacement and acceleration as response parameters.

Results and Discussion

A very useful representation for design purposes is obtained by analysing the displacement response as a function of the TMD period for a given base structure period. In this case, the displacement response of the base SDOF coupled with the TMD exhibits a clear minimum value that corresponds to the optimal tuning condition of the system. By comparing this response with the displacement obtained for the uncontrolled SDOF system (i.e., without TMD), it is possible to evaluate the effectiveness of the vibration control device. In several cases the presence of the TMD leads to a significant reduction in displacement; however, for certain combinations of the TMD vibration period the displacement of the base structure may increase instead.

A similar analysis was performed considering the structural response in terms of spectral acceleration. The results confirm that the tuning relationship between the structural period and the TMD period strongly influences the dynamic response of the system. When the auxiliary mass is properly tuned, a clear reduction in acceleration demand is observed with respect to the uncontrolled SDOF system. Consequently, these results can be used as a practical design tool when the reduction of acceleration represents the main performance objective. The results of the study are further summarized in terms of normalized displacement and acceleration, obtained by dividing the response of the controlled system by the corresponding response of the uncontrolled SDOF system. The legend adopted for these representations is reported in Table 2.

It is important to clarify the range of base structure periods considered in the analyses. Although the complete parametric investigation explored a wide range of structural periods from 0 to 4.0 s, the analyses used to develop design-oriented charts focus on a narrower interval between 0.50 s and 1.50 s, with increments of 0.20 s. This choice is motivated by the observation that it is uncommon for existing buildings to exhibit fundamental vibration periods exceeding 1.5 s. Since the proposed abaci are intended for application to existing structures, the investigation was concentrated within this more realistic range of structural periods. The results indicate that the damping ratio of the TMD has a limited influence on both displacement and acceleration of the base structure until the optimal tuning condition is reached. After this point, however, a significant dispersion among the response curves can be observed.

Another important observation concerns the influence of the mass ratio on the optimal tuning condition. For relatively small mass ratios, the minimum displacement response is obtained when the vibration period of the TMD is approximately equal to that of the base structure. Conversely, for larger mass ratios the optimal condition shifts toward higher values of the TMD period, which may reach values close to 1 s when the mass ratio is equal to 0.40.

The normalized response diagrams derived from the parametric analyses can therefore be used as practical design tools for the dimensioning of non-conventional TMD systems applied to existing structures. In the design phase, the main characteristics of the building, namely the structural mass m_b and the fundamental period T_b, are typically known. For a given value of the mass ratio $\overline{m}$, the optimal design solution can be obtained using the abaci derived from the parametric analysis, which allows the corresponding value of T_{tmb} to be determined.

Overall, the results show that properly tuned systems can significantly improve the structural response. In particular, reductions in maximum top displacement greater than 30% and decreases in peak acceleration exceeding 40% were observed. In some cases the increase in seismic performance could be dramatically high. As an example, when in the existing structure there is the development of a soft storey mechanism, which nowadays is avoided by adopting specific design procedure (Montuori et al. 2015, Montuori et al. 2017), the superelevation allows to avoid the development of this brittle and low dissipative mechanism. Similarly, the problem of residual drift is avoided (Montuori et al 2021, Montuori et al. 2024) because the structure remains in elastic range.

Table 2. Legend of figure 4 to 8

		T_{base} [s]					
		0.5	0.7	0.9	1.1	1.3	1.5
TMD damping	0.15						
	0.2						
	0.25						
	0.3						

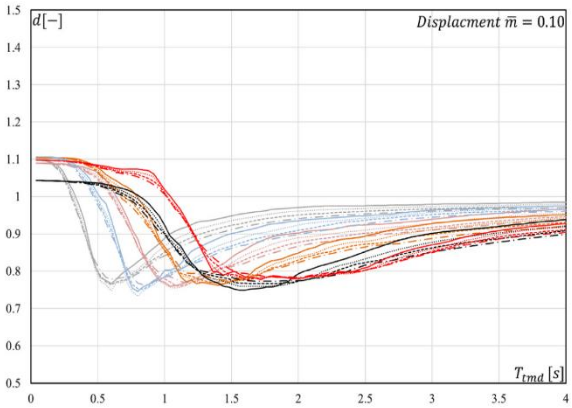

Figure 4. Dimensionless displacement (left) and dimensionless acceleration (right) with $\overline{m} = m_{tmb}/m_b = 0.1$

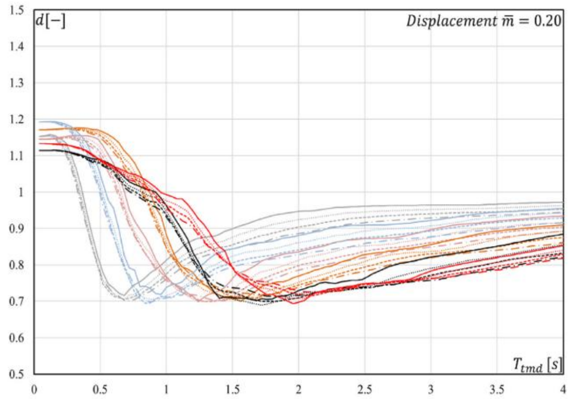

Figure 5. Dimensionless displacement (left) and dimensionless acceleration (right) with $\overline{m} = m_{tmb}/m_b = 0.2$

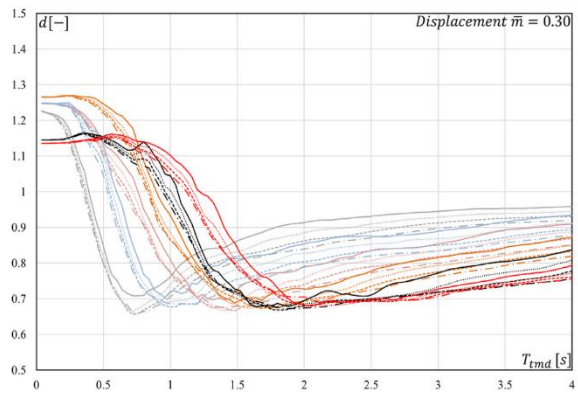

Figure 6. Dimensionless displacement (left) and dimensionless acceleration (right) with $\overline{m} = m_{tmb}/m_b = 0.3$

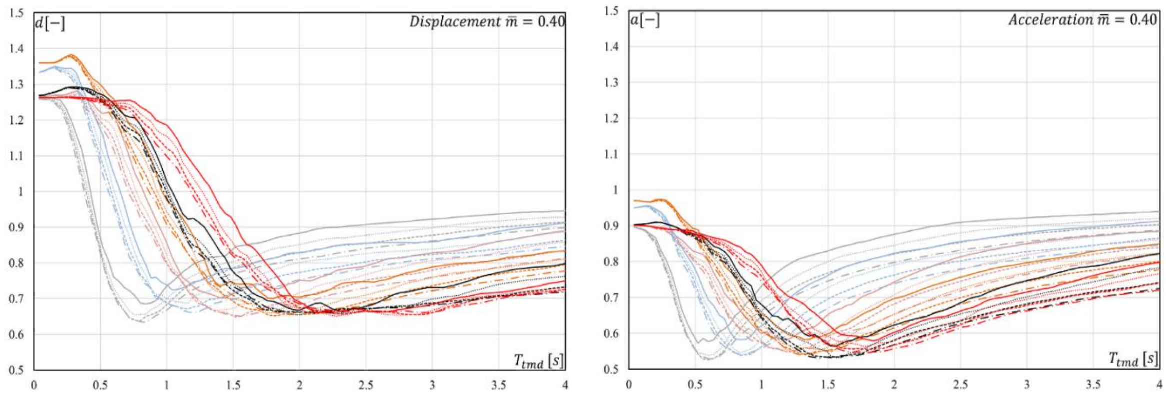

Figure 6. Dimensionless displacement (left) and dimensionless acceleration (right) with $\overline{m} = m_{tmb}/m_b = 0.4$

Conclusion

This study investigates the use of non-conventional Tuned Mass Dampers (TMDs) characterized by high mass ratios as a strategy for the seismic retrofitting of existing buildings, particularly those designed according to outdated seismic design criteria. The proposed concept is based on the addition of one or more new storeys above the existing structure, separated from it through the installation of seismic isolation devices.

An extensive parametric investigation was carried out using a simplified mechanical model with two degrees of freedom (1 + 1 DOFs). The analyses considered a wide set of seismic ground motions while varying the main governing parameters of the system, namely the mass ratio and the damping properties of the TMD. The results were summarized in the form of design-oriented charts (designer-friendly abaci) developed to optimize both displacement and acceleration responses of the base structure. These charts provide a practical tool for identifying the optimal configuration of the system during the design phase.

From a practical perspective, the proposed strategy is particularly attractive for existing buildings designed without seismic provisions. In many of these structures the safety factors with respect to vertical loads are often greater than unity, whereas the capacity to resist horizontal seismic actions is generally insufficient. This condition frequently makes it possible to introduce one or more additional storeys without exceeding the vertical load capacity of the existing structural system.

An additional important aspect concerns the economic feasibility of the intervention. The construction of new habitable volumes generated by the superelevation can represent a substantial economic benefit which, when feasible, may offset a significant portion of the retrofit costs and in some cases even cover the entire intervention, resulting in a net economic advantage.

Furthermore, when strengthening interventions on the existing structure are required, they are typically limited to the vertical structural elements rather than to the beams. In fact, following the introduction of the superelevation-based TMD system, seismic demands acting on the structure are reduced while vertical loads increase. As a consequence, the strengthening demand tends to shift from beams to columns. This aspect is particularly advantageous because interventions on columns are generally simpler and more cost-effective compared with strengthening of beam elements.

Overall, the results demonstrate that the adoption of non-conventional high-mass-ratio TMD systems represents a promising approach for improving the seismic performance of existing buildings. The proposed design abaci provide a practical framework for supporting retrofit interventions aimed at reducing both displacement and acceleration demands during earthquake excitation. The findings highlight the significant potential of high-mass-ratio TMDs for the seismic upgrading of buildings designed with outdated criteria, contributing to the development of more resilient built environments.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

Funding

* This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Basic Sciences and Technology (www.icbast.net) held in Konya/Türkiye on April 02-05, 2026.

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To cite this article:

Montuori, R., Nastri, E., & Marrazzo, P.R., (2026). High mass ratio tuned mass dampers obtained through building superelevations for seismic retrofit. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 40,* 296-303.