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NOVEL LARGE MASS DAMPING APPROACHES FOR EFFICIENT TALL BUILDING DESIGN

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Abstract: *Traditional approaches for the design of tall buildings under wind and earthquake loads are widely recognized to result in less efficient and resilient solutions when compared to modern techniques involving the use of supplementary damping systems. To this end, the benefits associated with mass damping systems versus alternative arrangements are being increasingly explored, not just to mitigate wind-induced response, for which they are the reference approach, but also to control seismic behaviour. This is even more the case for redundant and large mass approaches that can result in improved dynamic response. This paper introduces a new generation of large mass damping systems which utilizes the own mass of the building as the damper mass. A usable portion of the building is allowed to experience minimum differential displacements with respect to the lateral-load resisting system. These movements are controlled via a series of springs to resist static loads, in parallel with fluid viscous dampers to control accelerations and dissipate energy. The performance of the system is investigated under both wind and seismic excitations for a series of target differential displacements and key performance indexes. The results show, that due to the large-mobilized mass, the system can generate significant levels of supplementary damping and, in turn, results in a drastically improved seismic response in all the performance indexes considered. With the benefits associated with mass damping systems, the proposed arrangement permits a new generation of tall buildings with an enhanced dynamic performance that can result in substantial savings for the overall structure as well as at substructure levels. Its implementation significantly reduces the carbon footprint of tall buildings and thus maximizes their positive contribution to urban infrastructure and contributes to the move towards a holistic Net Zero approach.*

Introduction

The traditional seismic design of buildings using capacity design principles, in which a series of elements are identified as structural fuses and dissipate energy via hysteresis behaviour, has demonstrated its ability to ensure building stability even under high seismic events. However, even if non-structural and repair costs have been significantly reduced since the adoption of performance-based design principles (Martinez-Paneda, 2023), recent high-magnitude events have shown these to still have significant drawbacks. This is especially the case when compared to buildings incorporating supplementary damping systems that can control the response not just in terms of building drifts and forces, but also reducing acceleration levels which are critical in terms of damage to non-structural elements (Kasai et al, 2012). The layer of resilience added by incorporating supplementary damping is in addition to the material savings and response reduction when compared to conventional design approaches (Soong & Spencer, 2002).

The benefits of adopting supplementary damping systems are even more accentuated for tall buildings as their design often tends to be governed by the requirement to limit wind-induced accelerations. Tall buildings damping systems can be broadly categorized into passive, active, or hybrid. Despite significant developments on all fronts, passive approaches, either distributed or mass systems, are still the most common due to their good performance, high reliability, and lower cost. Distributed systems include elastomeric or fluid viscous dampers as diagonal braces over the height of the building. While the system performance depends on the overall buildings flexibility to generate sufficient differential motions at the ends of the dampers, it has the significant advantage of creating a redundant system that can maximize the benefits of the added damping. Mass systems, particularly Tuned Mass Dampers (TMD) are, however, the most commonly implemented tall building damping system (Lago et al, 2019).

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The popularity of TMDs originates from their favourable performance, relative simplicity, and adaptability to be added late in the design once wind tunnel test results become available. However, they exhibit a series of limitations: (i) they occupy a large usable and valuable space at the top; (ii) the large added mass requires strengthening of the existing frame; (iii) their specific frequency tuning is more suitable for wind rather than seismic, due to higher mode contribution; (iv) inability to reach a resonant response when subjected to a pulse or random base-excitation; (v) high tunning sensitivity that can result in significant loss of performance; and (vi) lack of redundancy leading to inability to use generated damping levels to reduce wind or seismic loads. Significant research effort has been focused on trying to address the limitations of conventional TMDs limitations (Aly, 2012).

This paper investigates the behaviour of a novel large mass damping arrangement referred to as ‘Integrated Damping System’ (IDS) that aims to overcome most conventional mass damper limitations, with minimum effect on the building usable area, while generating large damping levels (Martinez-Paneda & Elghazouli, 2020). The system performance and behaviour is investigated through its application within a 250 m tall illustrative building under both wind and seismic excitations. The concept is described and compared to alternative modern mass damper systems, and its performance evaluated under both seismic and wind excitations.

Large mass damping systems

Passive mass dampers have significant benefits when compared to alternative damping systems due to several factors including their relative simplicity, cost, maintenance, and reliability. The main parameter influencing the performance of a TMD is the ratio between damper mass and main mass. However, in conventional systems, this is typically limited to 0.5%-1% due to practical limitations, hence resulting in supplementary damping levels within the range of 1%-4%. To this end, the benefits of developing a system that can mobilize a larger damper mass can be shown through the response of an idealized 2DOF system where the main structure is represented as a single degree of freedom (SDOF) with an attached TMD as depicted in Figure 1. In the figure, c represents the damper coefficient, k is the lateral stiffness, m is the mass, u is the displacement, and p is the excitation of the main structure. The subscripts d represents the properties corresponding to the vibration absorber as opposed to those of the main mass. This simplified representation is widely used and is valid provided that the main frequencies are well separated as is generally the case for tall buildings (Warburton, 1982).

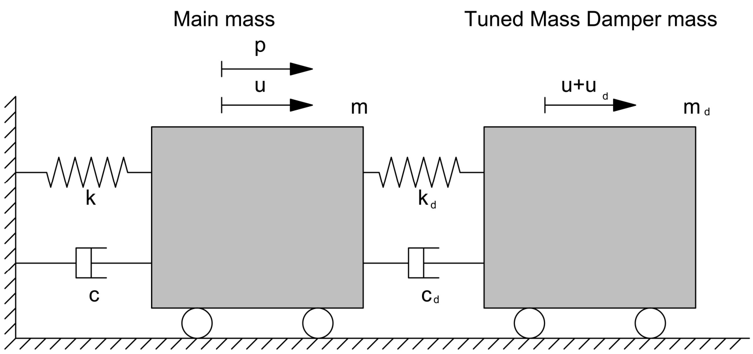


Figure 1: Simplified two degree of freedom representation of a single degree of freedom structure with an attached tuned mass damper.

The response under a dynamic excitation can be investigated, assuming optimum parameters following Den Hartog’s formulation (Warburton, 1982), and neglecting the damping of the main structure due to its reduced magnitude and rearranging the equation of motion. Based on this, the relationship between the ratio of the maximum displacement amplitudes of the damped mass and the main mass (u_d/u) for a specific level of equivalent damping can be derived (Equation 1).

$$\frac{u_d}{u} = \sqrt{\left(\frac{2\xi}{\mu}\right)^2 - 1} \qquad (1)$$

Where μ is the mass ratio between the damper mass and main mass, and ξ is the damping ratio with respect to the critical. As depicted in Figure 2(a), as the mass ratio increases the required relative displacement between both masses decreases for a given target damping ratio. Moreover, while a conventional TMD provides most of the response mitigation by introducing an out-of-phase force, as the damper mass increases and the behaviour approaches that of a continuously damped system, the dependency on frequency tunning becomes less relevant as significant energy is dissipated by the dampers. This can be investigated by comparing the amplitude of the steady-state response of the 2DOF from Figure 1 under harmonic excitation for different mass ratios under different input frequency ratios with Equation 2 as shown in Figure 2. In these representations, u_{st} is the displacement of the main mass under a static load of magnitude p; g is the ratio of the excitation frequency, Ω, to the main mass natural frequency, ω; and f is the ratio between the damper mass frequency, ω_d, and the main mass frequency, ω.

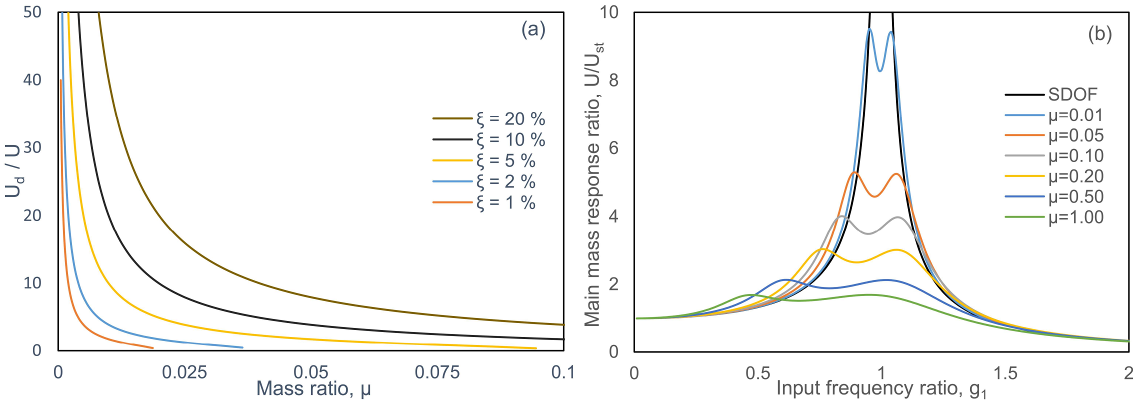


Figure 2: a) Variation in ratio of maximum displacement amplitudes with respect to mass ratio, b) Response with varying mass ratio under harmonic main mass excitation.

$$\frac{u}{u_{st}} = \frac{\sqrt{\left(1-\frac{g^2}{f^2}\right)^2 + 4\left(\frac{\xi_d g}{f}\right)^2}}{Z} \tag{2}$$

$$Z = \left\{\left[\frac{g^4}{f^2} - \frac{g^2}{f^2} - g^2(1+\mu) - 4\frac{\xi\xi_d g^2}{f} + 1\right]^2 + \left[2\frac{\xi g^3}{f} + 2\frac{\xi_d g^3}{f}(1+\mu) - 2\frac{\xi_d g}{f} - 2\xi g\right]^2\right\}^{\frac{1}{2}} \tag{3}$$

From the results, it is evident that the response improves with increased mass ratio and that, for relatively high values of μ, the system effectiveness is less sensitive to the resonant effect and it is able to reduce the response of the structure over a wider frequency range. This has the clear benefit of not only achieving a more robust response but also being able to control the response of the system in higher frequency modes. Given the significant benefits, significant research effort has been placed on exploring the feasibility of proposing large-mass tuned mass dampers. The "roof-garden TMD" proposes the use of a heavy roof garden (Matta & Stefano, 2009). Other variations include merging the concept of TMDs and floor isolation systems (FIS) to propose either a series of "suspended slab systems" (Mahmoud & Chulahwat, 2015) or in-floor TMDs (Xiang & Nishitani, 2014). While this combined TMD-FIS system has the benefit of mobilizing part of the building mass as damper mass, it also shares some of the limitations of both systems, such as the requirement to duplicate the floor structure, and the need to have all floors perfectly tuned. Alternative variations include the so-called "mega subconfiguration", applicable to buildings with a mega-frame as lateral load-resisting system, on which an interior substructure dissipates energy by either tunning it to act as a TMD or through conventional distributed elements vibrating as a shear frame. By mobilizing a large portion of the building own mass, it is able to greatly improve the dynamic performance. However, the system capability to is limited as the substructure needs to be finely tuned to behave as a TMD, and hence it can only apply to interior portions, and with special detailing to avoid pounding with the surrounding frame (Feng & Mita, 1995). Additional attempts include concepts such as using the mass of a double-skin façade as the damper mass of a TMD (Moon, 2011), or, in a slightly different approach and moving beyond conventional

TMDs, the concept of shifting base isolation higher up the building leading to partial mass isolation systems (Ziyaeifar & Noguchi, 1998).

The novel Integrated Damping System described in this paper bases its formulation on the two main concepts illustrated in Figure 2: (i) if a sufficiently large mass is mobilized as damper mass, only a small differential displacement is required to achieve large levels of damping, and (ii) that for such a case, the system is able to mitigate the response even if not perfectly tuned.

Integrated Damping System

The Integrated Damping System (IDS) departs from the traditional idea of tuning the damper mass to the building first natural period like a conventional TMD, as this becomes unnecessary when mobilizing a relatively large mass. Rather than adding extra mass, the system uses a portion of the building own usable mass to generate damping via the differential displacement between the lateral load-resisting system and the movable portion. The damper mass is connected via springs working in parallel with fluid viscous dampers. The springs control the level of differential displacements between the damper mass and the main building to ensure it fits within acceptable serviceability limits and provide the static output to resist the wind load static component. In contrast to other systems, which are tuned to match the optimum parameters of conventional TMDs, the IDS is able to use an exterior portion of the building as damper mass and hence increasing the mass mobilized and drastically enhancing the flexibility of the system. The fluid viscous dampers (FVDs) also play a key role, working in parallel with the springs, to act as the energy-dissipating elements and control accelerations within the movable portion. The system is based on the well-known notion that provided accelerations are controlled, building movements are not a limiting condition from a human perception standpoint (Kareem, 1983).

The novel concept of the IDS is effectively able to overcome most conventional TMDs limitations while providing significantly larger levels of damping. Beyond not adding any additional mass, it avoids occupying valuable space at the top of the building by integrating within every floor plate of the movable portion. The system does not rely on the overall building flexibility and hence, contrary to most distributed systems, does not have a height limitation and is applicable to both tall and supertall buildings. Due to the large mass ratio, the system is insensitive to detuning and provides a redundant and robust response that can effectively mitigate both wind and seismic excitations and account for the added damping to reduce the strength design loads hence bringing substantial savings to both the superstructure and the foundations.

Typical application

The performance and behaviour of the IDS is assessed by investigating the response of an illustrative 250 m tall building. The building is conceived as a mega-frame with four vertical communication cores at the corners of a central square formed by a series of 12 m deep trusses. The trusses join the cores together to create a mega-frame and split the tower vertically transferring the gravity loads from the five independent vertically stacked office blocks to the concrete cores (Figure 3). The decision to place the cores on the outside of the usable office space creates a column-free office space that forms an independent volume from the lateral load-resisting system. This arrangement enables each block to move independently from the concrete cores with a clearly defined joint line and without affecting the lateral stiffness of the building. As shown in Figure 3, the blocks are rotated at 90 degrees with respect to their contiguous counterparts to create a terrace space, improve across-wind response, and enable different views across the height.

Although all the blocks could be designed as movable and hence achieve substantial response improvement in all modes, which could potentially be beneficial for high-seismic zones, only the top two are considered herein in order to maximize the performance efficiency while simplifying the detailing requirements. Moreover, each block is defined to move in one direction only so as to further simplify the detailing while still ensuring that the system would generate damping in all directions. Movement is enabled by providing a sliding joint to support the office floors at the core interface both for gravity and transversal wind loads. Gravity loads of the office floors are transferred to the columns supported on the trusses between blocks. The floor lateral stability is provided in-plane by connecting every floor plate to the core by a series of springs in parallel with fluid viscous dampers (FVDs) (Figure 4).

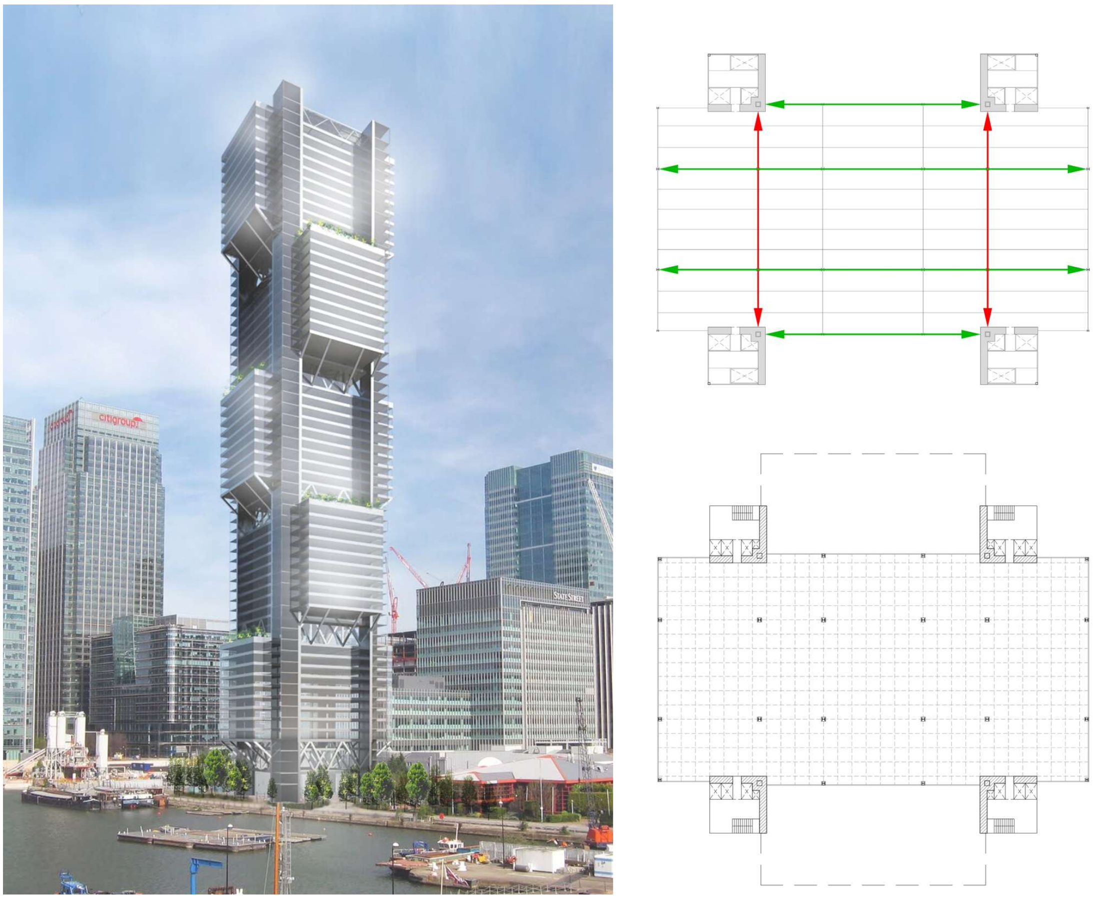


Figure 3: Tower visualization with architectural floor plan and structural plan with highlighted primary (red) and secondary (green) trusses.

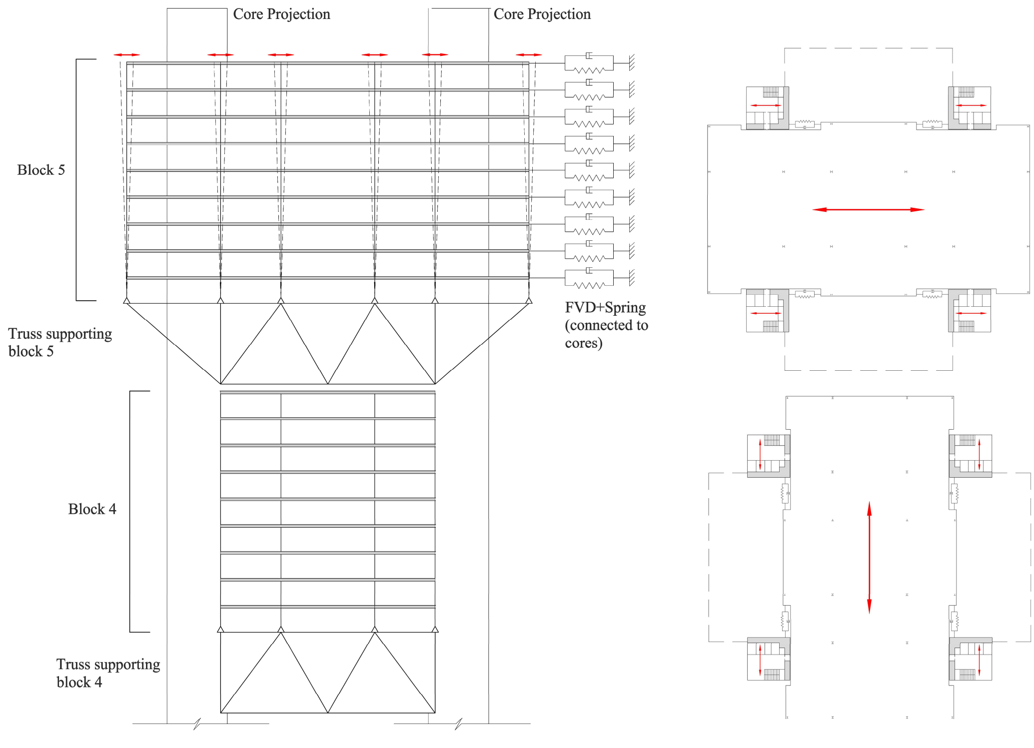


Figure 4: Integrated Damping System implementation diagrams.

Although a mega-frame building was used in the current investigation, it is worth noting that, as the movable mass can resist static wind loads, the system can be extrapolated to other tall building typologies without a height limit. Alternative applications could include central core buildings where the perimeter columns at the top section are designed not to take any lateral loads and hence the floor plate around the core can be mobilized as a damper mass with the columns providing gravity support.

Model definition and loading conditions

The illustrative building is investigated via a simplified 2DOF model with lumped masses at the centroid of every office block and the corresponding core section as shown in Figure 5, where $k_{c,i}$ and $m_{c,i}$ represent the stiffness and mass of the mega-frame and cores, respectively, at each block i, $m_{f,i}$ the mass of each block, k_R a rigid link and c_i and $k_{f,i}$ the damper and stiffness of the damped floor. The simplified model is matched to the illustrative building mass, stiffness properties, and modal characteristics within a 5% difference for the first three translational modes.

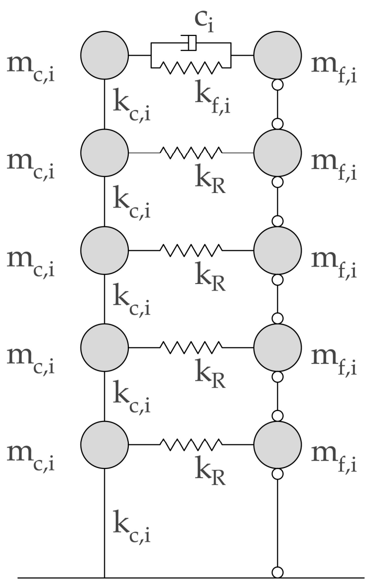


Figure 5: Simplified 2DOF model.

The model is investigated using the finite element analysis software SAP2000. Nonlinear time-history analyses were performed using direct integration with the Newmark method for every iteration to account for the damper velocity-dependent behaviour. The tower was modelled with an intrinsic damping value of 1%. Fluid viscous dampers were set as linear dampers following the Maxwell model of viscoelasticity with a damper exponent, α, equal to 1 (Martinez-Paneda & Elghazouli, 2021).

To assess the performance of the system, the additional equivalent damping that can be generated was first determined followed by an assessment of the response under realistic wind and seismic excitations. The level of supplementary damping was evaluated using the half-power bandwidth method by performing a sweep excitation over a range around the first natural frequency to obtain the peak response for each input frequency under steady-state conditions. The wind response of the system was assessed using a set of realistic along wind and across-wind time-history forcing functions from the wind tunnel test data of a similar tall building which is currently under construction.

The seismic behaviour of the system was also examined under seven real earthquake acceleration time histories selected and scaled to closely match the EN1998-1 Type 1 Soil C target spectrum (CEN, 2004), with a peak ground acceleration of 0.25 g, magnitude, M, ranging from 5.0 to 7.5, a fault distance from 10 to 100 km, shear wave velocity, V_s, from 180 to 800 m/s, and minimizing the root mean square deviation, DRMS, over a period range from 0.2T to T, where T is the first natural period (Table 1). The selected scaled time histories are shown in Figure 6.

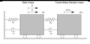
NGA Record	Earthquake Name	 Date	M	Distance to Fault (km)	Vs30 (m/s)	PGA (g)	Scale Factor	D_{RMS}
00127 T	Friuli, Italy	1976-09-11	5.5	15.1	339	0.04	7.55	0.05
00138 L	Tabas, Iran	1978-09-16	7.4	24.1	339	0.11	2.89	0.07
00302 T	Irpinia, Italy	1980-11-23	6.2	22.7	339	0.10	3.19	0.06
00564 L	Kalamata, Greece	1986-09-13	6.2	11.2	339	0.25	1.24	0.05
01144 L	Gulf of Aqaba	1995-11-22	7.2	43.3	355	0.10	3.18	0.07
01155L	Kocaeli, Turkey	1999-08-17	7.5	60.45	275	0.10	2.97	0.10
01163L	Kocaeli, Turkey	1999-08-17	7.5	58.3	425	0.09	3.41	0.13

Table 1: Seismological and scaling data for the seven selected records.

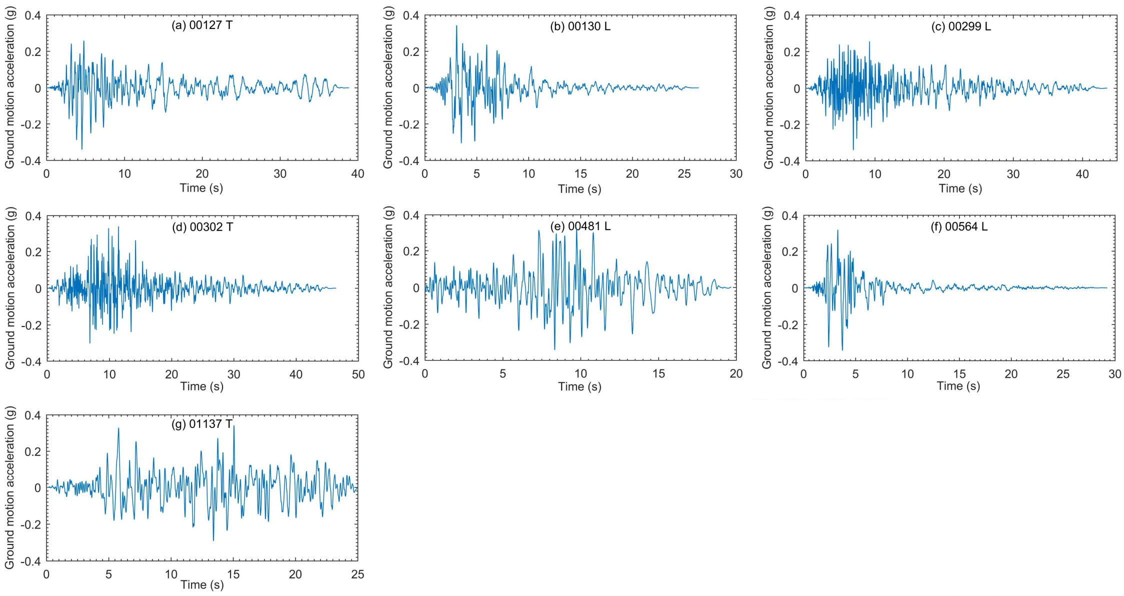


Figure 6: Scaled acceleration time histories for the seven selected records (a-g).

Performance assessment

The stiffness of the IDS is one of the key parameters that influence its performance. Two values are considered in this study with respect to the differential displacement between both masses under the 50-year London static Eurocode wind force: a lower bound of 25 mm and an upper bound of 250 mm, representing relatively small and comparatively large displacements respectively. It is worth noting that the upper bound of 250 mm has been set to meet practical limitations in terms of movement perception rather than services or finishes within movement joints limitations, which can be adapted to accommodate such movements with minimal additional cost. By performing an initial sensitivity study to obtain the optimum damper coefficient to maximize additional damping, it was shown that the small and large displacement cases can achieve up to 2.9 % and 56.0 % equivalent damping, respectively, as shown in Figure 7.

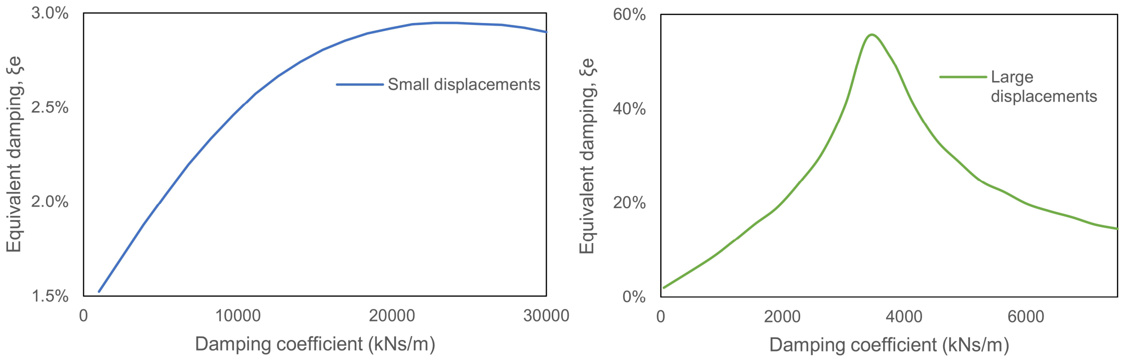


Figure 7: Equivalent damping versus damper coefficient for spring stiffnesses allowing a maximum displacement of 25 mm (a) and 250 mm (b), under the design mean wind load.

Wind response

The results showed that the system was very effective in mitigating the wind response of the building. The applied wind load function, together with the top displacement for the small displacements case, the large displacement case, and those corresponding to the fixed configuration are shown in Figure 8 for a segment of 100 s corresponding to the peak response from the nearly 4 hours of the whole record. In the along direction, the top displacement is reduced by 16% and 23% for the small and large displacement cases. An even larger improvement occurs in the across-wind response, which usually drives the design of tall buildings and is characterized by a dynamic response, where the top displacements reduce by 33% and 58% respectively.

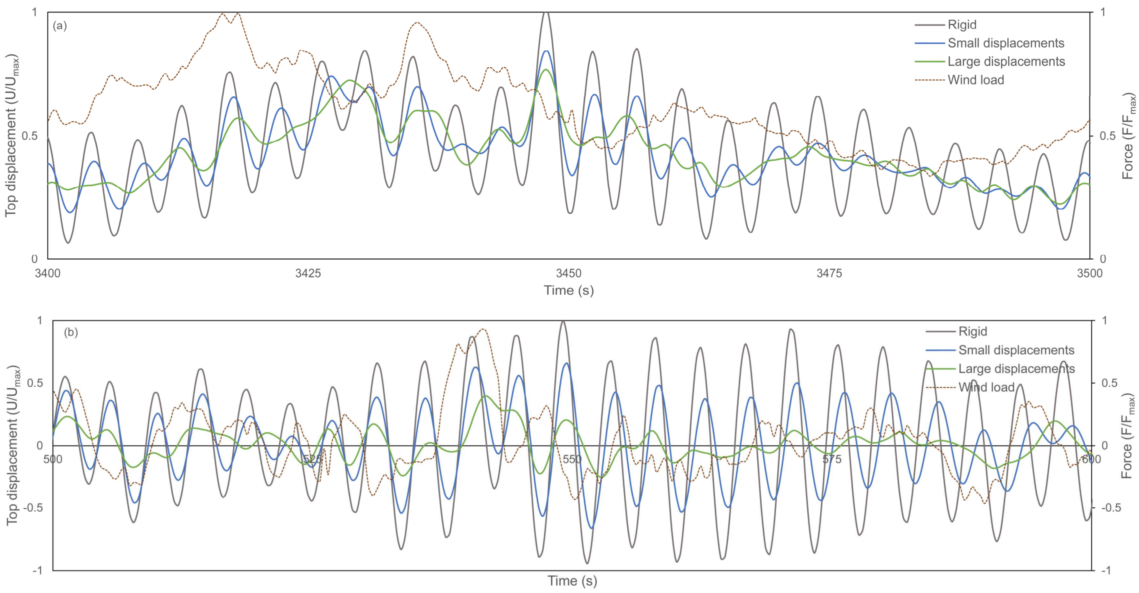


Figure 8: Top displacement ratio and force ratio time history for along wind (a) and across-wind (b) wind time history excitation.

The improvement in response is noticeable in the reduction of wind-induced accelerations. From the time-history results, the accelerations are reduced by 37 % for both cases of the small displacement, with 46% for along wind, and 54% for across-wind in the large displacement case.

Seismic response

Significant performance improvement was also obtained when the tower was subjected to the seven real seismic excitations, compared to the response of a fixed configuration. This can be shown by plotting the top displacement for the 00302 T (Irpinia) record in Figure 9. From the averaged response over the seven records, depicted in Figure 10, it is evident that the system is able to reduce the top displacement by up to 15% and 50% for the small and large displacement cases, respectively.

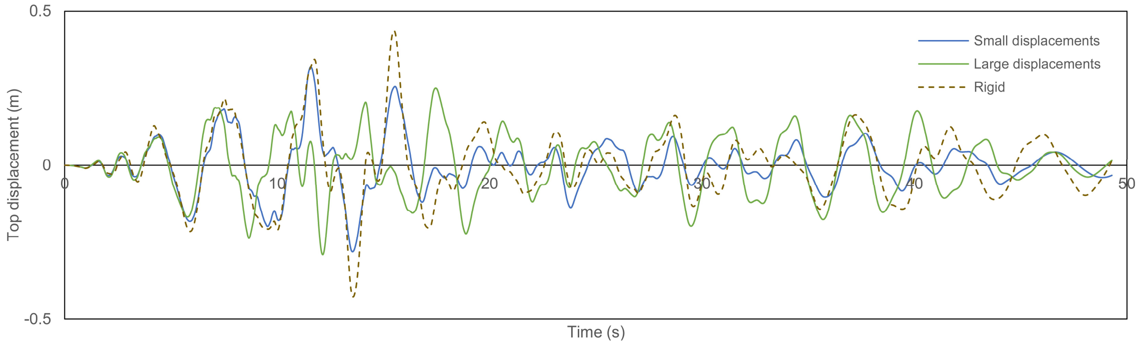


Figure 9: Displacement time history of the tower against the (c) Irpinia 00302 T acceleration record for the small and large displacement cases.

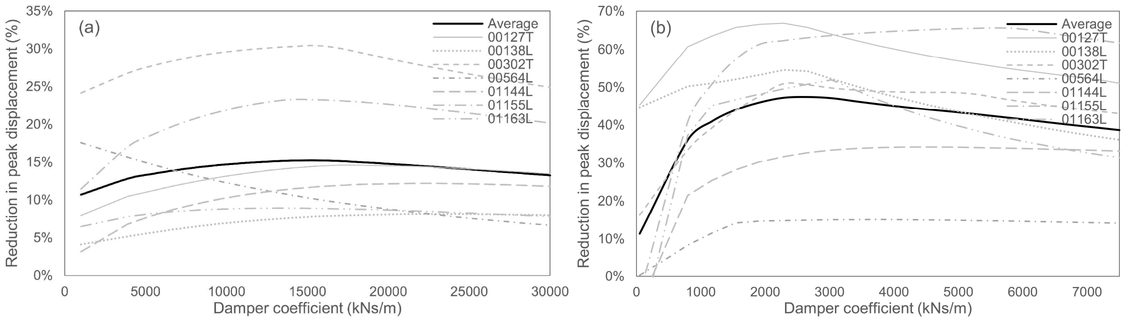


Figure 10: Reduction in top displacement versus damper coefficient values for the seven selected records, for a maximum differential displacement of 25 mm (a) and 250 mm (b).

Figure 10 also shows that the response of the system varies depending on the seismic record. This can be linked to the limitation of conventional TMD in dealing with pulse excitations. Nonetheless, in the case of the IDS, response enhancement is still obtained when compared to the fixed case, albeit with different degrees depending on the excitation characteristics. A similar improvement can be observed for other performance indexes such as inter-storey drifts, accelerations, and overall base shear, thus validating the significant potential of the IDS to improve the dynamic response of tall buildings. The implementation of such a redundant system would not only lead to more resilient designs but could also bring substantial savings in both the superstructure and foundations hence reducing the overall carbon footprint of the building.

Conclusions

This paper has described a novel damping system that originates from a departure from the conventional concept of considering a structure as a single unit. Instead, a building is conceived as a series of interacting constituents that can control the overall dynamic response by mobilizing the structure own mass as a damper mass. Due to the large mass that can be mobilized, the system is able to generate large levels of supplementary damping with minimum differential displacements. The movable portion is connected via a series of springs acting in parallel with fluid viscous dampers to resist static wind loads while effectively controlling accelerations and dissipating energy.

The concept was investigated using an illustrative 250 m tall building under two design scenarios corresponding to small and large differential displacements between the portion denoted as damper mass and the main mass of the building. The system was able to achieve 2.9% to 56% equivalent damping. The capacity of the concept to control the dynamic response was examined using realistic wind and seismic time history excitations. The top displacements under wind were reduced in a range from 16% to 58%, with a clear improvement in effectiveness when mitigating across-wind excitations due to their dynamic nature. Wind-induced acceleration reduction also ranged from 37% to 54%. The seismic response, verified through seven earthquake records, also proved considerably mitigated. Beyond large reductions in accelerations in the movable floors, which are partly isolated from the excitation, the average top displacement reductions ranged from 15% to 50% for the small and large differential displacement cases, respectively.

Overall, the results of this study ascertain the significant benefits that the IDS concept can provide when implemented in a tall building. As a redundant damping system applicable without a practical height limit, the approach has the potential of offering considerable savings both in the foundations and superstructure by reducing the strength and stiffness demands, hence achieving more efficient and resilient designs.

References

Martinez-Paneda, M. (2023) Towards a holistic Performance-Based Design Approach. *The Structural Engineer*, 101, 1. doi: 10.56330/RSHC9924

Kasai, K., Pu, W.C. & Wada, A. (2012) Response of Passively-Controlled Tall Buildings in Tokyo during 2011 Great East Japan Earthquake. *15th WCEE*, Lisbon, Portugal.

Soong, T.T. & Spencer, B.F. (2002) Supplemental energy dissipation: state-of-the-art and state-of-the-practice. *Engineering Structures*, 24, pp 243-249.

Lago, A., Trabucco, D. & Wood, A. (2019) Damping Technologies for Tall Buildings. Butterworth-Heinemann, doi: 10.1016/C2017-0-01327-7

Aly, A.M. (2015) Proposed robust tuned mass damper for response mitigation in buildings exposed to multidirectional wind. Structural Design of Tall and Special Buildings, 23(9), pp 664-691. doi: 10.1002/tal.1068.

Warburton, G.B. (1982). Optimum Absorber Parameters for various combinations of response and excitation parameters. *Earthquake Engineering and Structural Dynamics*, 10, 381-401.

Martinez-Paneda, M. and Elghazouli, A. Y. (2020) “An integrated Damping System for Tall Buildings”, *The Structural Design of Tall and Special Buildings*, 29(7), e1724, doi: 10.1002/tal.1724

Matta, E. & De Stefano, A. (2009) Seismic performance of pendulum and translational roof-garden TMDs. *Mechanical Systems and Signal Processing*. 23, 908-921.

Feng, M. & Mita, A. (1995) Vibration Control of Tall Buildings Using Mega SubConfiguration. Journal of Engineering Mechanics, ASCE; 121;1082-1088.

Xiang, P. & Nishitani A. (2014) Seismic vibration control of building structures with multiple tuned mass damper floors integrated. Earthquake Engineering and Structural Dynamics; 43, pp 909-925. doi: 10.1002/eqe.2379

Mahmoud, H. & Chulahwat, A. (2015) Response of building systems with suspended floor slabs under dynamic excitations. Engineering Structures, 104, 155-173.

Moon, K.S. (2011) Structural Design of Double Skin Facades as Damping Devices for Tall Buildings. Procedia Engineering, 14, pp 1351-1358. Doi: 10.1016/j.proeng.2011.07.170

Ziyaeifar, M. & Noguchi, H. (1998) Partial Mass Isolation in tall buildings. Earthquake Engineering and Structural Dynamics, 27, pp 49-65.

Martinez-Paneda, M & Elghazouli, A. Y. (2021) Optimal application of fluid viscous dampers in tall buildings incorporating integrated damping systems. The Structural Design of Tall and Special Buildings, 30(17), e189, doi: 10.1002/tal.1892

CEN. Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings. 2004, BS EN 1998-1-4:2004